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DIAGRAMMATIC CHARACTERISATION OF ENRICHED ABSOLUTE COLIMITS

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ABSTRACT. We provide a diagrammatic criterion for the existence of an absolute colimit in the context of enriched category theory.

An *absolute colimit* is one preserved by any functor; the class of absolute colimits was characterised for ordinary categories by Paré [4] and for enriched ones by Street [5]. For categories enriched over a monoidal category $\mathcal{V}$ or bicategory $\mathcal{W}$, the appropriate colimits are the weighted colimits of [6], and Street's characterisation is in fact one of the class of *absolute weights*: those weights φ such that φ-weighted colimits are preserved by any functor. This is different to Paré's result, which gives a diagrammatic characterisation of when a particular cocone is absolutely colimiting. In this note, we give a result in the enriched context which is closer in spirit to Paré's than to Street's. This result is very useful in practice, but seems not to be in the literature; we set it down for future use.

1. The result

1.1. BACKGROUND. We work in the context of bicategory-enriched category theory; see [6], for example. $\mathcal{W}$ will denote a bicategory whose homs are locally small, complete and cocomplete categories, and which is *biclosed*, meaning that for each 1-cell $A\colon x \to y$ in $\mathcal{W}$, the composition functors $A\otimes(\text{–})\colon \mathcal{W}(z,x) \to \mathcal{W}(z,y)$ and $(\text{–})\otimes A\colon \mathcal{W}(y,z) \to \mathcal{W}(x,z)$ have right adjoints $[A,\text{–}]$ and $\langle A,\text{–}\rangle$ respectively.

A $\mathcal{W}$*-category* $\mathcal{A}$ comprises a set $\operatorname{ob}\mathcal{A}$ of objects; for each $a \in \operatorname{ob}\mathcal{A}$ an object $\epsilon a \in \operatorname{ob}\mathcal{W}$, the *extent* of a; for each pair of objects a, b, a hom-object $\mathcal{C}(b,a) \in \mathcal{W}(\epsilon a, \epsilon b)$; and identity and composition 2-cells $\iota\colon I_{\epsilon a} \to \mathcal{C}(a,a)$ and $\mu\colon \mathcal{C}(c,b)\otimes\mathcal{C}(b,a) \to \mathcal{C}(c,a)$ satisfying the expected axioms. A $\mathcal{W}$*-profunctor* $M\colon \mathcal{A} \looparrowright \mathcal{B}$ is given by objects $M(b,a) \in \mathcal{W}(\epsilon a, \epsilon b)$ and action maps $\mu\colon \mathcal{B}(b',b)\otimes M(b,a)\otimes\mathcal{A}(a,a') \to M(b',a')$ satisfying unitality and associativity axioms. A *profunctor map* $M \to M'\colon \mathcal{A} \looparrowright \mathcal{B}$ comprises maps $M(b,a) \to M'(b,a)$ compatible with the actions by $\mathcal{A}$ and $\mathcal{B}$. The identity profunctor $\mathcal{A}\colon \mathcal{A} \looparrowright A$ has components $\mathcal{A}(b,a)$ with action given by composition in $\mathcal{A}$. For profunctors $M\colon \mathcal{A} \looparrowright \mathcal{B}$ and $N\colon \mathcal{B} \looparrowright \mathcal{C}$ with $\mathcal{B}$ small, the tensor product $N \otimes_{\mathcal{B}} M\colon \mathcal{A} \looparrowright \mathcal{C}$

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has components given by coequalisers

$$\textstyle\sum_{b,b'} N(c,b) \otimes \mathcal{B}(b,b') \otimes M(b',a) \rightrightarrows \sum_b N(c,b) \otimes M(b,a) \twoheadrightarrow (N \otimes_{\mathcal{B}} M)(c,a)$$

and actions by $\mathcal{C}$ and $\mathcal{A}$ inherited from N and M. Small $\mathcal{W}$-categories, profunctors and profunctor maps comprise a bicategory $\mathcal{W}$-**Mod**. There is a full embedding $\mathcal{W} \to \mathcal{W}$-**Mod** sending X to the $\mathcal{W}$-category X with one object $\star$ with $\epsilon(\star) = X$ and $X(\star,\star) = I_X$.

If $\mathcal{A}$ and $\mathcal{B}$ are $\mathcal{W}$-categories, then a *$\mathcal{W}$-functor* $F\colon \mathcal{A} \to \mathcal{B}$ comprises an extent-preserving assignation on objects, together with 2-cells $\mathcal{C}(b,a) \to \mathcal{D}(Fb,Fa)$ subject to two functoriality axioms. If $F\colon \mathcal{A} \to \mathcal{C}$ and $G\colon \mathcal{B} \to \mathcal{C}$ are $\mathcal{W}$-functors then there is an induced profunctor $\mathcal{C}(G,F)\colon \mathcal{A} \relbar\joinrel\mapstochar\joinrel\rightarrow \mathcal{B}$ with components $\mathcal{C}(G,F)(b,a) = \mathcal{C}(Gb,Fa)$ and action derived from the action of F and G on homs and composition in $\mathcal{C}$.

Given profunctors $M\colon \mathcal{A} \relbar\joinrel\mapstochar\joinrel\rightarrow \mathcal{B}$, $N\colon \mathcal{B} \relbar\joinrel\mapstochar\joinrel\rightarrow \mathcal{C}$ and $L\colon \mathcal{A} \relbar\joinrel\mapstochar\joinrel\rightarrow \mathcal{C}$ with $\mathcal{B}$ small, a profunctor map $u\colon N \otimes_{\mathcal{B}} M \to L$ is said to *exhibit M as $[N,L]$* if every map $f\colon N \otimes_{\mathcal{B}} K \to L$ is of the form $u \circ (N \otimes_{\mathcal{B}} \bar{f})$ for a unique $\bar{f}\colon K \to M$; while it is said to *exhibit N as $\langle M, L\rangle$* if every $f\colon K \otimes_{\mathcal{B}} M \to L$ is of the form $u \circ (\bar{f} \otimes_{\mathcal{B}} M)$ for a unique $\bar{f}\colon K \to N$.

Given $\varphi\colon \mathcal{A} \relbar\joinrel\mapstochar\joinrel\rightarrow \mathcal{B}$ in $\mathcal{W}$-**Mod** and a functor $F\colon \mathcal{B} \to \mathcal{C}$, a *$\varphi$-weighted colimit* of F is a functor $Z\colon \mathcal{A} \to \mathcal{C}$ and profunctor map $a\colon \varphi \to \mathcal{C}(F,Z)$ such that for each $C \in \mathcal{C}$, the map

$$\varphi \otimes_{\mathcal{A}} \mathcal{C}(Z,C) \xrightarrow{a \otimes_{\mathcal{A}} 1} \mathcal{C}(F,Z) \otimes_{\mathcal{A}} \mathcal{C}(Z,C) \xrightarrow{\mu} \mathcal{C}(F,C) \tag{1}$$

exhibits $\mathcal{C}(Z,C)$ as $[\varphi, \mathcal{C}(F,C)]$. A functor $G\colon \mathcal{C} \to \mathcal{D}$ *preserves* this colimit just when the composite $\varphi \to \mathcal{C}(F,Z) \to \mathcal{D}(GF,GZ)$ exhibits GZ as a φ-weighted colimit of GF; the colimit is *absolute* when it is preserved by all functors out of $\mathcal{C}$. [5] proves that φ-weighted colimits are absolute if and only if φ admits a right adjoint in $\mathcal{W}$-**Mod**.

Dually, given $\psi\colon \mathcal{B} \relbar\joinrel\mapstochar\joinrel\rightarrow \mathcal{A}$ in $\mathcal{W}$-**Mod** and a functor $F\colon \mathcal{B} \to \mathcal{C}$, a *$\psi$-weighted limit* of F is a functor $Z\colon \mathcal{A} \to \mathcal{C}$ and map $b\colon \psi \to \mathcal{C}(Z,F)$ such that for each $C \in \mathcal{C}$, the map

$$\mathcal{C}(C,Z) \otimes_{\mathcal{A}} \psi \xrightarrow{1 \otimes_{\mathcal{A}} b} \mathcal{C}(C,Z) \otimes_{\mathcal{A}} \mathcal{C}(Z,F) \xrightarrow{\mu} \mathcal{C}(C,F)$$

exhibits $\mathcal{C}(C,Z)$ as $\langle \psi, \mathcal{C}(C,Z)\rangle$. Absoluteness of limits is defined as before; now every limit weighted by $\psi\colon \mathcal{B} \relbar\joinrel\mapstochar\joinrel\rightarrow \mathcal{A}$ is absolute if and only if ψ has a *left* adjoint in $\mathcal{W}$-**Mod**.

1.2. Theorem. *Let $\varphi\colon \mathcal{A} \relbar\joinrel\mapstochar\joinrel\rightarrow \mathcal{B}$ admit the right adjoint $\psi\colon \mathcal{B} \relbar\joinrel\mapstochar\joinrel\rightarrow \mathcal{A}$ in $\mathcal{W}$-**Mod**, and let $F\colon \mathcal{B} \to \mathcal{C}$ and $Z\colon \mathcal{A} \to \mathcal{C}$ be $\mathcal{W}$-functors. There is a bijective correspondence between data of the following forms:*

- *(a) A map $a\colon \varphi \to \mathcal{C}(F,Z)$ exhibiting Z as a φ-weighted colimit of F;*
- *(b) A map $b\colon \psi \to \mathcal{C}(Z,F)$ exhibiting Z as a ψ-weighted limit of F;*
- *(c) Maps $a\colon \varphi \to \mathcal{C}(F,Z)$ and $b\colon \psi \to \mathcal{C}(Z,F)$ such that the following two squares commute in $\mathcal{W}$-**Mod**$(\mathcal{A},\mathcal{A})$ and $\mathcal{W}$-**Mod**$(\mathcal{B},\mathcal{B})$:*

$$\begin{tikzcd} \mathcal{A} \arrow[r, "\eta"] \arrow[d, "Z"'] & \psi \otimes_{\mathcal{B}} \varphi \arrow[d, "b \otimes_{\mathcal{B}} a"] \\ \mathcal{C}(Z,Z) & \mathcal{C}(Z,F) \otimes_{\mathcal{B}} \mathcal{C}(F,Z) \arrow[l, "\mu"] \end{tikzcd} \qquad \begin{tikzcd} \varphi \otimes_{\mathcal{A}} \psi \arrow[r, "\varepsilon"] \arrow[d, "a \otimes_{\mathcal{A}} b"'] & \mathcal{B} \arrow[d, "F"] \\ \mathcal{C}(F,Z) \otimes_{\mathcal{A}} \mathcal{C}(Z,F) \arrow[r, "\mu"'] & \mathcal{C}(F,F) \end{tikzcd} \; . \tag{2}$$

Proof. Suppose first given (a); consider the composite profunctor map

$$\varphi \otimes_{\mathcal{A}} \mathcal{C}(Z, F) \xrightarrow{a \otimes_{\mathcal{A}} 1} \mathcal{C}(F, Z) \otimes_{\mathcal{A}} \mathcal{C}(Z, F) \xrightarrow{\mu} \mathcal{C}(F, F) \ . \tag{3}$$

Evaluating in the second variable at any $a \in \mathcal{A}$ yields the map (1) exhibiting $\mathcal{C}(Z, Fa)$ as $[\varphi, \mathcal{C}(F, Fa)]$; it follows easily that (3) exhibits $\mathcal{C}(Z, F)$ as $[\varphi, \mathcal{C}(F, F)]$. Applying this universality to the composite $\varepsilon \circ F \colon \varphi \otimes_{\mathcal{A}} \psi \to \mathcal{B} \to \mathcal{C}(F, F)$ yields a unique map $b \colon \psi \to \mathcal{C}(Z, F)$ making the right square of (2) commute; we must show that the left one does too. Arguing as before shows that

$$\varphi \otimes_{\mathcal{A}} \mathcal{C}(Z, Z) \xrightarrow{a \otimes_{\mathcal{A}} 1} \mathcal{C}(F, Z) \otimes_{\mathcal{A}} \mathcal{C}(Z, Z) \xrightarrow{\mu} \mathcal{C}(F, Z) \tag{4}$$

exhibits $\mathcal{C}(Z, Z)$ as $[\varphi, \mathcal{C}(F, Z)]$. It thus suffices to show that the left square of (2) commutes after applying the functor $\varphi \otimes_{\mathcal{A}} (-)$ and postcomposing with (4); which follows by a short calculation using commutativity in the right square and the triangle identities.

So from the data in (a) we may obtain that in (c), and the assignation is injective, since b is uniquely determined by universality of a and commutativity on the right of (2). For surjectivity, suppose given a and b as in (c); we must show that a exhibits Z as a φ-weighted colimit of F, in other words, that for each $C \in \mathcal{C}$, the map (1) exhibits $\mathcal{C}(Z, C)$ as $[\varphi, \mathcal{C}(F, C)]$, or in other words, that for each map $f \colon \varphi \otimes_{\mathcal{A}} K \to \mathcal{C}(F, C)$, there is a unique map $\bar{f} \colon K \to \mathcal{C}(Z, C)$ such that $f = \mu \circ (a \otimes_{\mathcal{A}} \bar{f}) \colon \varphi \otimes_{\mathcal{A}} K \to \mathcal{C}(F, Z) \otimes_{\mathcal{A}} \mathcal{C}(Z, C) \to \mathcal{C}(F, C)$. For existence, we let $\bar{f}$ be the composite

$$K \cong \mathcal{A} \otimes_{\mathcal{A}} K \xrightarrow{\eta \otimes_{\mathcal{A}} 1} \psi \otimes_{\mathcal{B}} \varphi \otimes_{\mathcal{A}} K \xrightarrow{b \otimes_{\mathcal{B}} f} \mathcal{C}(Z, F) \otimes_{\mathcal{B}} \mathcal{C}(F, C) \xrightarrow{\mu} \mathcal{C}(Z, C) \ ; \tag{5}$$

now rewriting with the right-hand square of (2) and using the triangle identities and F's preservation of units shows that $f = \mu \circ (a \otimes_{\mathcal{A}} \bar{f})$. For uniqueness, let $g \colon K \to \mathcal{C}(Z, C)$ also satisfy $f = \mu \circ (a \otimes_{\mathcal{A}} g)$. Substituting into (5) shows that $\bar{f}$ is the composite

$$K \cong \mathcal{A} \otimes_{\mathcal{A}} K \xrightarrow{\eta \otimes_{\mathcal{A}} 1} \psi \otimes_{\mathcal{B}} \varphi \otimes_{\mathcal{A}} K \xrightarrow{b \otimes_{\mathcal{B}} a \otimes_{\mathcal{A}} g} \mathcal{C}(Z, F) \otimes_{\mathcal{B}} \mathcal{C}(F, Z) \otimes_{A} \mathcal{C}(Z, C) \xrightarrow{\mu} \mathcal{C}(Z, C) \ ;$$

which by rewriting with the left square of (2) and using Z's preservation of identities is equal to g. This proves the equivalence (a) $\Leftrightarrow$ (c); now (b) $\Leftrightarrow$ (c) follows by duality. ∎

1.3. Examples. We first consider examples wherein $\mathcal{W}$ is the one-object bicategory corresponding to a monoidal category $\mathcal{V}$.

- Let $\mathcal{V} = \mathbf{Set}$, and let φ be the weight for splittings of idempotents. The result recovers the bijection, for an idempotent $e \colon A \to A$, between: maps $p \colon A \to B$ coequalising e and 1_A; maps $i \colon B \to A$ equalising e and 1_A; and pairs (i, p) with $pi = 1_A$ and $ip = e$.

- Let $\mathcal{V} = \mathbf{Set}_*$, and let φ be the weight for an initial object. The result recovers the bijection in a pointed category between: initial objects; terminal objects; and objects X with $1_X = 0_X$.

- Let $\mathcal{V} = \mathbf{Ab}$, and let φ be the weight for binary coproducts. The result recovers the bijection, for objects A, B in a pre-additive category, between: coproduct diagrams $i_1 \colon A \to Z \leftarrow B \colon i_2$; product diagrams $p_1 \colon A \leftarrow Z \to B \colon p_2$; and tuples (i_1, i_2, p_1, p_2) such that $p_j i_k = \delta_{ik}$ and $i_1 p_1 + i_2 p_2 = 1_Z$.

- Let $\mathcal{V} = \bigvee\text{-}\mathbf{Lat}$, and let φ be the weight for J-fold coproducts (for J a small set). The result recovers the bijection, for objects $(A_j : j \in J)$ in a sup-lattice enriched category, between: coproduct diagrams $(i_j \colon A_j \to Z)_{j \in J}$; product diagrams $(p_j \colon Z \to A_j)_{j \in J}$; and families $(i_j)_{j \in J}$ and $(p_j)_{j \in J}$ with $p_j i_k = \delta_{jk}$ and $\bigvee_j i_j p_j = 1_Z$.

- Let $\mathcal{V} = k\text{-}\mathbf{Vect}$ for k a field of characteristic zero, let G be a finite group, and let $\varphi \colon k \to\!\!\!\!\!\!+\, kG$ be the trivial right kG-module k. By Burnside's Lemma, φ has a right adjoint $kG \to\!\!\!\!\!\!+\, k$ given by the trivial left kG-module k. Now the result recovers the bijection, for a G-representation A in a k-linear category, between: maps $p \colon A \to Z$ exhibiting Z as an object of coinvariants of A; maps $i \colon Z \to A$ exhibiting Z as an object of invariants of A; and pairs of maps (i, p) with $pi = 1_Z$ and $ip = \frac{1}{|G|} \Sigma_{g \in G}\, g$.

We conclude with two examples where $\mathcal{W}$ is a genuine bicategory.

- Let $(\mathcal{C}, j)$ be a subcanonical site, and let $\mathcal{W}$ denote the full sub-bicategory of $\mathbf{Span}(\mathbf{Sh}(\mathcal{C}))^{\mathrm{op}}$ on objects of the form $\mathcal{C}(-, X)$. To any prestack $p \colon \mathcal{E} \to \mathcal{C}$ over $\mathcal{C}$, we may (as in [1]) associate a $\mathcal{W}$-category with objects those of $\mathcal{E}$, extents $\epsilon(a) = p(a)$, and hom-object from a to b given by the span $\mathcal{C}(-, pa) \leftarrow \mathcal{E}(a, b) \to \mathcal{C}(-, pb)$ in $\mathbf{Sh}(\mathcal{C})$; here $\mathcal{E}(a, b)(x)$ is the set of all triples (f, g, θ) with $f \colon pa \leftarrow x \to pb \colon g$ in $\mathcal{C}$ and $\theta \colon f^*(a) \to g^*(b)$ in $\mathcal{E}_x$ (note that $\mathcal{E}(a, b)$ is a sheaf by the prestack condition).

  For any cover $(f_i \colon U_i \to U)_{i \in I}$ in $\mathcal{C}$, we have a $\mathcal{W}$-category $R[f]$ with object set I, extents $\epsilon(i) = U_i$ and hom-objects $R[f](j, i) = \mathcal{C}(-, U_j) \leftarrow \mathcal{C}(-, U_j \times_U U_i) \to \mathcal{C}(-, U_i)$. There is a profunctor $\varphi \colon U \to\!\!\!\!\!\!+\, R[f]$ with components given by the spans $\varphi(i, \star) = \mathcal{C}(-, U_i) \leftarrow \mathcal{C}(-, U_i) \to \mathcal{C}(-, U)$. Writing $\psi \colon R[f] \to\!\!\!\!\!\!+\, U$ for the reverse profunctor, it is not hard to see that $\varphi \dashv \psi$ (in fact they are adjoint pseudoinverse).

  The result now says the following. Given a prestack $p \colon \mathcal{E} \to \mathcal{C}$, a cover $(f_i \colon U_i \to U)$ in $\mathcal{C}$, and a family of spans $p_{ij} \colon a_i \leftarrow a_{ij} \to a_j \colon q_{ij}$ in $\mathcal{E}$ whose legs are cartesian over the projections $U_i \leftarrow U_i \times_U U_j \to U_j$, there is a bijection between: cocones $(h_i \colon a_i \to a)$ in $\mathcal{E}$ over the f_i's that are colimiting for the diagram comprised of the p_{ij}'s and q_{ij}'s; universal objects $a \in \mathcal{E}_U$ equipped with vertical maps $f_i^*(a) \to a_i$ fitting into double pullback squares

$$\begin{tikzcd} f_i^*(a) \arrow[d] & \cdot \arrow[l] \arrow[r] \arrow[d] & f_j^*(a) \arrow[d] \\ a_i & a_{ij} \arrow[l, "p_{ij}"'] \arrow[r, "q_{ij}"'] & a_j \end{tikzcd} ;$$

  and objects $a \in \mathcal{E}_U$ equipped with a family of maps $(h_i \colon a_i \to a)$ cartesian over the f_i's. This generalises [6, Proposition 5.2(b)][1].

[1]The proposition numbering here is taken from the TAC reprint.

- Let $\mathcal{W}$ denote the bicategory whose objects are sets, and whose hom-category $\mathcal{W}(X,Y)$ is the category of finitary functors $\mathbf{Set}/Y \to \mathbf{Set}/X$; note that $\mathcal{W}(X,Y) \simeq [\mathbf{Fam}(Y) \times X, \mathbf{Set}]$, where $\mathbf{Fam}(Y)$ has as objects, finite lists of elements of Y, and as maps $(y_0,\dots,y_m) \to (z_0,\dots,z_n)$, functions $f\colon [m] \to [n]$ such that $y_i = z_{f(i)}$. To any cartesian multicategory M (i.e., a *Gentzen multicategory* in the sense of [3]) we may associate a $\mathcal{W}$-category $\mathcal{M}$ whose objects of extent X are X-indexed families of objects of M, and whose hom-object between families $(a_x)_{x\in X}$ and $(b_y)_{y\in Y}$ is the presheaf
$$\mathcal{M}((b_y),(a_x))(y_0,\dots,y_m;x) = M(b_{y_0},\dots,b_{y_m};a_x)$$
in $[\mathbf{Fam}(Y) \times X, \mathbf{Set}]$; reindexing along maps in Y makes use of the cartesianness of the multicategory structure. Composition and units in $\mathcal{M}$ follow from those in M.

  Given a finite set $X = \{x_0,\dots,x_n\}$, let $\varphi\colon 1 \to\!\!\!\!\!+ X$ be the $\mathcal{W}$-profunctor whose unique component is the representable $y(x_0,\dots,x_n;\star) \in [\mathbf{Fam}(X)\times 1, \mathbf{Set}]$. This has a right adjoint $\psi\colon X \to\!\!\!\!\!+ 1$ whose unique component is the presheaf $\Sigma_{x\in X} y(\star;x) \in [\mathbf{Fam}(1) \times X, \mathbf{Set}]$. The result now establishes a bijection, for any finite family $(a_0,\dots,a_n)$ of objects in a cartesian multicategory M, between data of the following three forms: first, an object a and a multimap $i \in M(a_0,\dots,a_n;a)$, composition with which induces bijections between $M(b_0,\dots,b_k,a,c_0,\dots,c_\ell;d)$ and $M(b_0,\dots,b_k,a_0,\dots,a_n,c_0,\dots,c_\ell;d)$; second, an object a and unary maps $p_j \in M(a;a_j)$, composition with which establishes bijections between $M(b_0,\dots,b_k;a)$ and $\Pi_j M(b_0,\dots,b_k;a_j)$; third, an object a and maps i and p_j as above such that $p_j \circ i = \pi_j \in M(a_0,\dots,a_n;a_j)$ and $i \circ (p_0,\dots,p_n) = 1_a \in M(a;a)$. This generalises [2, Proposition 3.5].

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