Fibrations of toposes from extensions of theories

Toposes in Como

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Idea

- For many special constructions of topological spaces, a structure preserving morphism between the presenting structures gives a map between the corresponding spaces. e.g.: a homomorphism $f : K \to L$ between two distributive lattices gives a map *in the opposite direction* between their spectra. The covariance or contravariance of this correspondence is a fundamental property of the construction.

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- In topos theory we can relativize this process: a presenting structure in an elementary topos $\mathcal{E}$ will give rise to a bounded geometric morphism $p\colon \mathcal{F} \to \mathcal{E}$, where $\mathcal{F}$ is the topos of sheaves over $\mathcal{E}$ for the space presented by the structure. Then we commonly find that the covariant or contravariant correspondence mentioned above makes every such p an opfibration or fibration in the 2-category of toposes and geometric morphisms.

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- Using the classifying toposes of geometric theories, we formalize this idea by the notion of fibration of toposes.

Johnstone fibrations in 2-categories

Comprehension 2-category

Suppose $\mathbb{K}$ is a 2-category and $\mathcal{D}$ is a class of bicarrable 1-cells in $\mathbb{K}$ which we shall call "display 1-cells". We form a 2-category $\mathbb{K}_{\mathcal{D}}$ whose

- 0-cells are of the form

$$\begin{array}{c} \overline{X} \\ {\scriptstyle x}\big\downarrow \\ \underline{X} \end{array}$$

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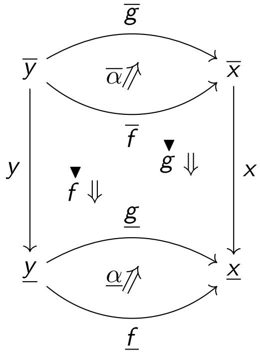
- 1-cells from y to x are of the form $f = \langle \overline{f}, \overset{\blacktriangledown}{f}, \underline{f} \rangle$

$$\begin{array}{ccc} \overline{y} & \xrightarrow{\overline{f}} & \overline{x} \\ {\scriptstyle y}\big\downarrow & \overset{\blacktriangledown}{f} \Downarrow & \big\downarrow{\scriptstyle x} \\ \underline{y} & \xrightarrow[\underline{f}]{} & \underline{x} \end{array}$$

  where $\overset{\blacktriangledown}{f} : x \circ \overline{f} \Rightarrow \underline{f} \circ y$ is an iso 2-cell in $\mathbb{K}$.

- 2-cells between 1-cells f and g are of the form $\alpha = \langle \overline{\alpha}, \underline{\alpha} \rangle$ where $\overline{\alpha} : \overline{f} \Rightarrow \overline{g}$ and $\underline{\alpha} : \underline{f} \Rightarrow \underline{g}$ are 2-cells in $\mathbb{K}$



in such a way that the obvious diagram of 2-cells commutes.

- Composition: by pasting

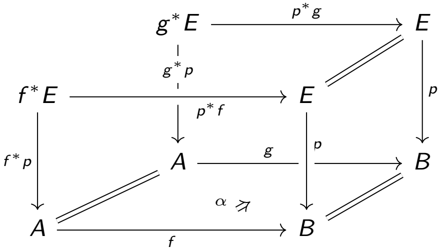
$\mathbb{K}_{\mathcal{D}}$ is a sub 2-category of $\mathbb{K}^{\downarrow}$ and the following diagram of 2-functors commutes.

$$\begin{array}{ccc} \mathbb{K}_{\mathcal{D}} & \hookrightarrow & \mathbb{K}^{\downarrow} \\ & {\scriptstyle \mathbb{B}\mathbf{ase}} \searrow \quad \swarrow {\scriptstyle \mathbb{C}\mathbf{od}} & \\ & \mathbb{K} & \end{array}$$

Johnstone's fibrations in 2-categories

DEFINITION (P. Johnstone, 93)

Suppose $\mathbb{K}$ is a 2-category. A 1-cell $p \colon E \to B$ is an (internal) **fibration** in $\mathbb{K}$ if it is bicarrable and for any 2-cell $\alpha \colon f \Rightarrow g \colon A \rightrightarrows B$ in $\mathbb{K}$, there exists a 1-cell $r(\alpha) \colon \underline{g}^*E \to \underline{f}^*E$, a 2-cell $\widetilde{\alpha} \colon p^*f \circ r(\alpha) \Rightarrow p^*g$, and a 2-cell $\tau(\alpha) \colon f^*p \circ r(\alpha) \Rightarrow g^*p$ satisfying *five axioms*.



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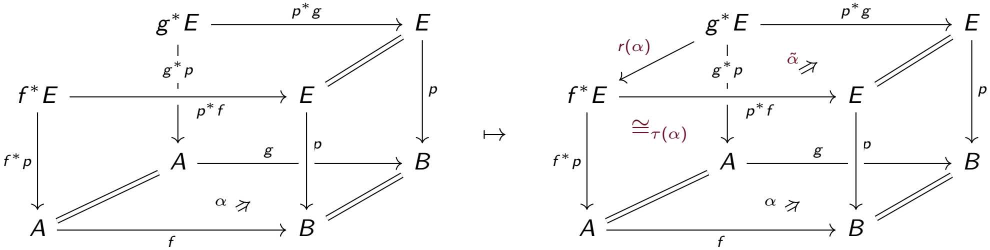

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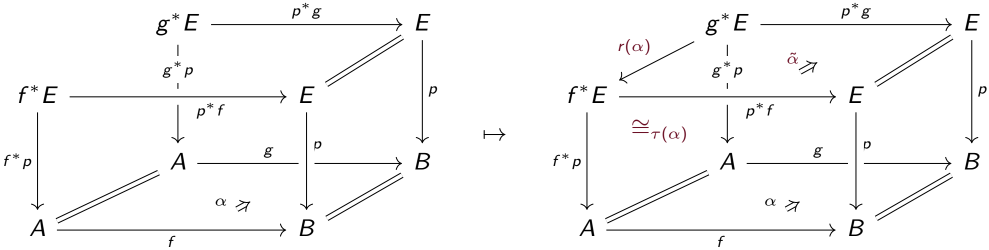
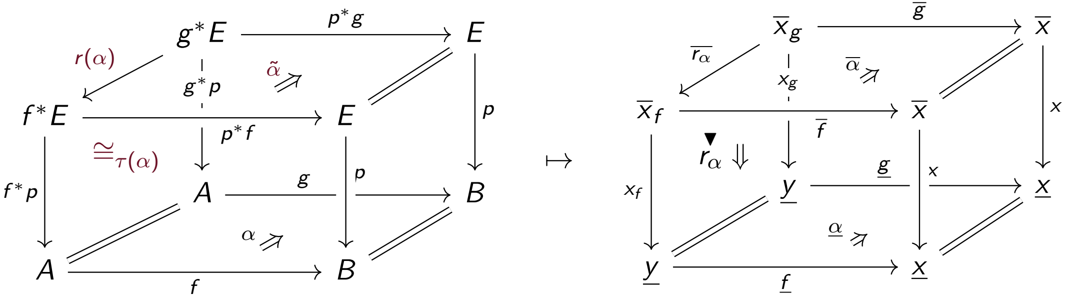


Peter Johnstone (1993). "Fibrations and partial products in a 2-category". In: *Applied Categorical Structures* vol.1.2, pp. 141–179. DOI: 10.1007/BF00880041

Remark

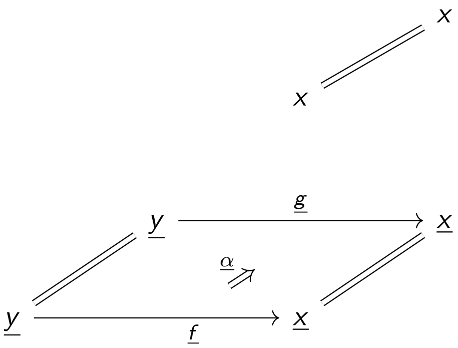
- This definition generalizes the definition of Grothendieck fibration of categories.
- The definition above is equivalent to the representable definition of fibration internal to a 2-category.
- Dually, *opfibrations* are defined by requiring a 1-cell $l(\alpha)\colon f^*E \to g^*E$ in the opposite direction of $r(\alpha)$.
- Johnstone's definition does not require strictness of the 2-category nor the existence of the structure of strict pullbacks and comma objects. Indeed, this definition is most suitable for weak 2-categories such as 2-category of toposes where we do not expect diagrams of 1-cells to commute strictly. This definition is also very flexible in terms of existence of bipullbacks.

Changing the notation ...



Simplifying Johnstone's definition

$$\mathbb{K}_{\mathcal{D}} \xrightarrow{\ \mathbb{B}\textbf{ase}\ } \mathbb{K}$$



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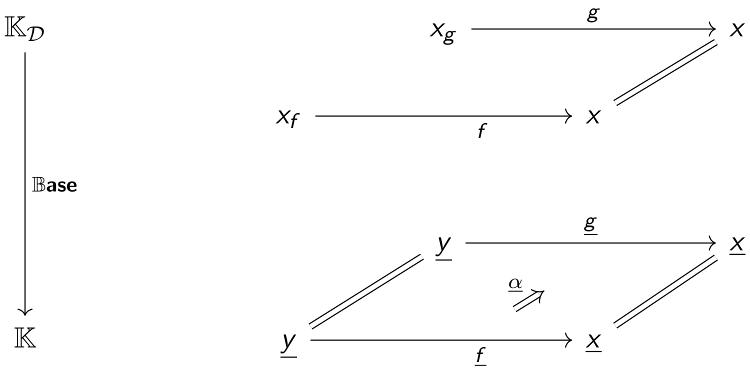

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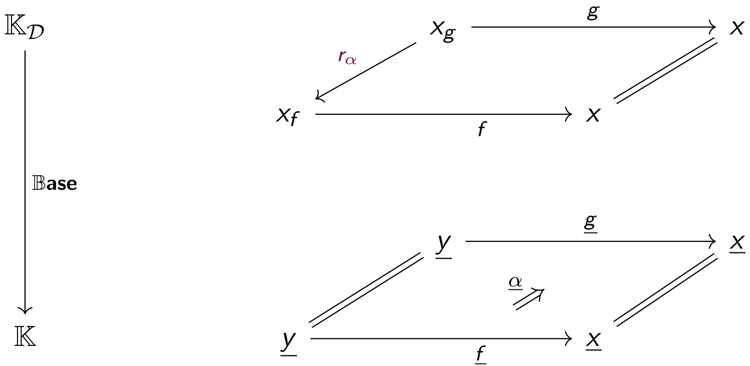

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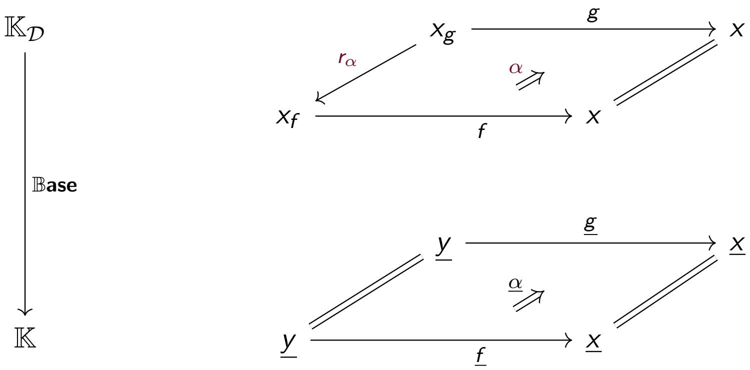
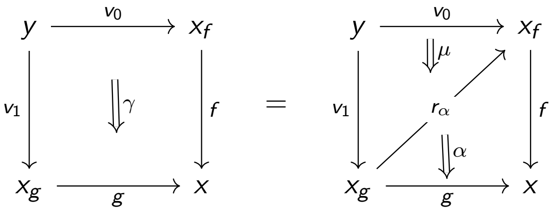


Axioms of Johnstone fibration

1. α lies over $\underline{\alpha}$,
2. lift of composition of composable 2-cells $\underline{\alpha}$ and $\underline{\beta}$ is isomorphic to composition of lifts α and β,
3. lift of identity of 2-cell is isomorphic to the lift of identity,
4. lift of (left) whiskering of $\underline{\alpha}$ with any 1-cell (with codomain $\underline{y}$) is the same as whiskering of of the lifts,
5. for any pair of vertical morphisms v_0 and v_1, any 2-cell $\gamma \colon f \circ v_0 \Rightarrow g \circ v_1$ uniquely factors through α



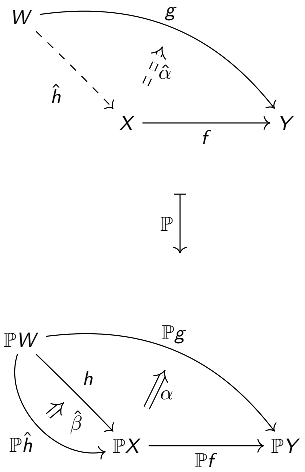
(Weak) cartesian 1-cells

Definition

Suppose $\mathbb{P}\colon \mathbb{X} \to \mathbb{C}$ is a 2-functor. A 1-cell $f\colon X \to Y$ in $\mathbb{X}$ is **cartesian** with respect to $\mathbb{P}$ whenever for each 0-cell W in $\mathbb{X}$ the following commuting square is a bipullback diagram in 2-category $\mathfrak{Cat}$ of categories.

$$\begin{array}{ccc} \mathbb{X}(W,X) & \xrightarrow{f_*} & \mathbb{X}(W,Y) \\ {\scriptstyle \mathbb{P}_{W,X}}\downarrow & \lrcorner & \downarrow{\scriptstyle \mathbb{P}_{W,Y}} \\ \mathbb{C}(\mathbb{P}W,\mathbb{P}X) & \xrightarrow[\mathbb{P}(f)_*]{} & \mathbb{C}(\mathbb{P}W,\mathbb{P}Y) \end{array}$$

Cartesian 1-cells in elementary terms

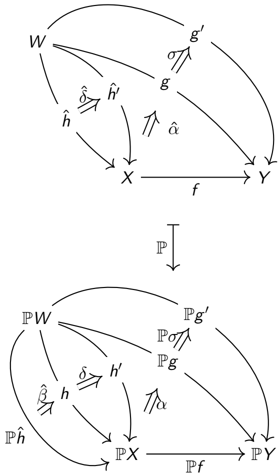


Input data:

1. $g\colon W \to Y$
2. $h\colon \mathbb{P}W \to \mathbb{P}X$
3. iso 2-cell $\alpha\colon \mathbb{P}(f) \circ h \Rightarrow \mathbb{P}(g)$

Output data:
(not necc. unique)

1. $\hat{h}\colon W \to X$
2. iso 2-cell $\hat{\alpha}\colon f\hat{h} \Rightarrow g$
3. iso 2-cell $\hat{\beta}\colon \mathbb{P}(\hat{h}) \Rightarrow h$
4. an equality of 2-cells
$\alpha \circ (\mathbb{P}(f) \centerdot \hat{\beta}) = \mathbb{P}(\hat{\alpha})$



Input data:

(1) $\sigma : g \Rightarrow g' : W \rightrightarrows Y$

(2) $\delta : h \Rightarrow h' : \mathbb{P}W \rightrightarrows \mathbb{P}X$

(3) iso 2-cells

$\alpha : \mathbb{P}(f) \circ h \Rightarrow \mathbb{P}(g)$

$\alpha' : \mathbb{P}(f) \circ h' \Rightarrow \mathbb{P}(g)$

(4) an equality of 2-cells

$\alpha' \circ (\mathbb{P}f \,.\, \delta) = \mathbb{P}(\sigma) \circ \alpha$

Output data:

(1) unique $\hat{\delta} : \hat{h} \Rightarrow \hat{h}'$

(2) an equality $\hat{\alpha}' \circ (f \,.\, \hat{\delta}) = \sigma \circ \hat{\alpha}$

(3) an equality $\delta \,.\, (\hat{\beta}) = \hat{\beta}' \circ \mathbb{P}\hat{\delta}$

Cartesian 2-cells

Definition

A 2-cell $\alpha\colon f \Rightarrow g\colon x \to y$ in $\mathbb{X}$ is **cartesian** if it is cartesian as a 1-cell for the functor $\mathbb{P}_{xy}\colon \mathbb{X}(x, y) \to \mathbb{C}(\mathbb{P}x, \mathbb{P}y)$.

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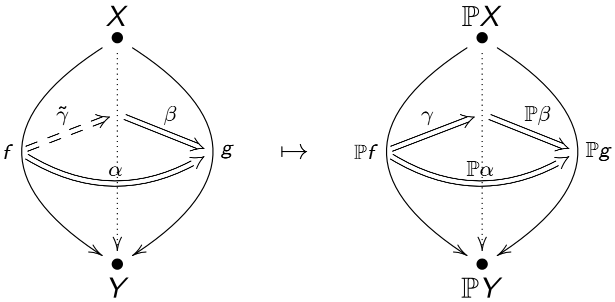
In elementary terms it means a 2-cell $\alpha \colon f \Rightarrow g \colon X \rightrightarrows Y$ is cartesian if for any given 1-cell $e \colon X \to Y$ and 2-cell $\beta \colon e \Rightarrow g$ with $\mathbb{P}\alpha = \mathbb{P}\beta \circ \gamma$ for some 2-cell γ, then there is a unique 2-cell $\tilde{\gamma}$ over γ such that $\alpha = \beta \circ \tilde{\gamma}$.



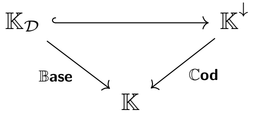
Proposition

A 1-cell $x\colon \overline{x} \to \underline{x}$ in $\mathbb{K}$ is a Johnstone fibration iff

1. every $\underline{f}\colon \underline{y} \to \underline{x} = \mathbb{C}\mathbf{od}(x)$ has a cartesian lift,
2. for every 0-cell y in $\mathbb{K}_{\mathcal{D}}$, the functor

   $$\mathbb{C}\mathbf{od}_{y,x}\colon \mathbb{K}_{\mathcal{D}}(y,x) \to \mathbb{K}(\mathbb{C}\mathbf{od}(y), \mathbb{C}\mathbf{od}(x))$$

   is a Grothendieck fibration of categories, and
3. whiskering on the left preserves cartesian 2-cells in $\mathbb{K}_{\mathcal{D}}$ between 1-cells with codomain x.



Relating internal fibrations in 2-categories to fibration of bicategories

Definition

Let $\mathbb{P}\colon \mathbb{X} \to \mathbb{C}$ be a 2-functor. $\mathbb{X}$ is **fibred over** $\mathbb{C}$ whenever

1. for any $X \in \mathbb{X}$ and $f\colon B \to \mathbb{P}X$ in $\mathbb{C}$, there is a weakly cartesian 1-cell $\widetilde{f}\colon \widetilde{B} \to X$ with $\mathbb{P}\widetilde{f} = f$;
2. $\mathbb{P}$ is locally fibred, i.e. $\mathbb{P}_{XY}\colon \mathbb{X}(X, Y) \to \mathbb{C}(\mathbb{P}X, \mathbb{P}Y)$ is a Grothendieck fibration of categories for all X, Y in $\mathbb{X}$
3. The horizontal composite of any two cartesian 2-cells is again cartesian.

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This definition is due to (Buckley, 2014) and he developes a theory of fibred bicategories in Mitchell Buckley (2014). "Fibred 2-categories and bicategories". In: vol. 218, pp. 1034–1074

The theory of fibred bicategories was also independently developed by (Bakovic, 2012) intrinsically to tricategories in Igor Bakovic (2012). "Fibrations in tricategories". In: *93rd Peripatetic Seminar on Sheaves and Logic, University of Cambridge*

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Remark

$\mathbb{K}_{\mathcal{D}}$ is fibred over $\mathbb{K}$ if every 1-cell in $\mathbb{K}_{\mathcal{D}}$ is a fibration in the sense of Johnstone.

2-categories (really bicategories) of toposes

- The 2-category $\mathcal{E}\mathfrak{Top}$ is the 2-category of elementary toposes, geometric morphisms, and natural transformations.
- The 2-category $\mathcal{G}\mathfrak{Top}$ is constructed from 2-category $\mathcal{E}\mathfrak{Top}$ by choosing the class of display morphisms to be bounded geometric morphisms of elementary toposes. So, $\mathcal{G}\mathfrak{Top} = \mathcal{E}\mathfrak{Top}_{\mathcal{D}}$ where $\mathcal{D}$ is the class of bounded geometric morphisms of elementary toposes.

$$
\begin{array}{ccc}
\mathcal{G}\mathfrak{Top} & \hookrightarrow & \mathcal{E}\mathfrak{Top}^{\downarrow} \\
{\scriptstyle \mathbb{B}\mathbf{ase}} \searrow & & \swarrow {\scriptstyle \mathbb{C}\mathbf{od}} \\
& \mathcal{E}\mathfrak{Top} &
\end{array}
$$

- A bounded geometric morphism $p \colon \mathscr{E} \to \mathscr{S}$ is a fibration of toposes if it is a fibration 0-cell in $\mathcal{G}\mathfrak{Top}$.

Classifying toposes as representing objects

- Consider the pseudofunctor

$$\mathbb{T}\text{-}\mathbf{Mod}\text{-} : (\mathcal{B}\mathfrak{Top}/\mathcal{S})^{\text{op}} \to \mathfrak{Cat}$$

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- Note that $\mathbb{T}\text{-}\mathbf{Mod}\text{-}(f \circ g) \cong (\mathbb{T}\text{-}\mathbf{Mod}\text{-}f) \circ (\mathbb{T}\text{-}\mathbf{Mod}\text{-}g)$
- The classifying topos $\mathscr{S}[\mathbb{T}]$ of a geometric theory/context $\mathbb{T}$ can be seen as a representing object for this pseudofunctor, i.e.

$$\mathcal{BTop}/\mathscr{S}(\mathscr{E}, \mathscr{S}[\mathbb{T}]) \simeq \mathbb{T}\text{-}\mathbf{Mod}\text{-}\mathscr{E}$$

naturally in $\mathscr{E}$.

Fibrations of toposes from extensionof theories

- Fix an elementary topos $\mathcal{S}$. Every geometric theory/ context $\mathbb{T}$ gives rise to an indexed category over $\underline{\mathbb{T}} : \mathcal{B}\mathfrak{Top}/\mathcal{S}$, where

$$\underline{\mathbb{T}}(\mathscr{E}) := \mathbb{T}\text{-}\mathbf{Mod}\text{-}(\mathscr{E}) = \text{category of models of } \mathbb{T} \text{ in } \mathscr{E}$$

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- Note that $\underline{\mathbb{T}}$ encapsulates data of all the models in all Grothendieck toposes (with base $\mathcal{S}$). Vickers calls them "elephant theories" after Johnstone, the sheer size of data encoded by them.
  Peter Johnstone (2002). "Sketches of an elephant: A topos theory compendium". In: *Oxford Logic Guides* vol.1.no.44, Oxford University Press
  Steven Vickers (2017). "Arithmetic universes and classifying toposes". In: *Cahiers de topologie et géométrie différentielle catégorique* vol.58.4, pp. 213–248. URL: http://cahierstgdc.com/wp-content/uploads/2018/01/Vickers-58-34.pdf

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- Of course not all elephant theories arise from contexts. For instance, given a bounded geometric morphism $p \colon \mathscr{E} \to \mathscr{S}$ and a context extension $U \colon \mathbb{T}_1 \to \mathbb{T}_0$ is a context extension and M is a strict model of context $\mathbb{T}$ in base topos $\mathcal{S}$, then $\mathbb{T}_1/M$ is an elephant theory but not a context, where

$$\underline{\mathbb{T}_1/M}(\mathscr{E}) :\,= \text{strict models of } \mathbb{T}_1 \text{ in } \mathscr{E} \text{ which reduce to } p^{\star}M \text{ via } U$$

- Fix an elementary topos $\mathcal{S}$. Every geometric theory/ context $\mathbb{T}$ gives rise to an indexed category over $\underline{\mathbb{T}} : \mathcal{B}\mathfrak{Top}/\mathcal{S}$, where

$$\underline{\mathbb{T}}(\mathscr{E}) := \mathbb{T}\text{-}\mathbf{Mod}\text{-}(\mathscr{E}) = \text{category of models of } \mathbb{T} \text{ in } \mathscr{E}$$

- Note that $\underline{\mathbb{T}}$ encapsulates data of all the models in all Grothendieck toposes (with base $\mathcal{S}$). Vickers calls them "elephant theories" after Johnstone, the sheer size of data encoded by them.
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- Certain elephant theories are geometric and have classifying toposes. $\underline{\mathbb{T}}$ and $\underline{\mathbb{T}_1/M}$ are such examples.

THEOREM (Vickers, 2017)

Suppose $U : \mathbb{T}_1 \to \mathbb{T}_0$ is a context extension. For any model M of $\mathbb{T}_0$ in a (base) topos $\mathcal{S}$, $\mathcal{S}[\mathbb{T}_1/M]$ is an $\mathcal{S}$-topos, and moreover, for any geometric (not necessarily bounded) morphism $\underline{f} : \mathcal{A} \to \mathcal{S}$, the classifying topos $\mathcal{A}[\mathbb{T}_1/\underline{f}^\star M]$ is got by bi-pullback of $\mathcal{S}[\mathbb{T}_1/M]$ along $\underline{f}$:

$$
\begin{array}{ccc}
\mathcal{A}[\mathbb{T}_1/\underline{f}^\star M] & \xrightarrow{\ \overline{f}\ } & \mathcal{S}[\mathbb{T}_1/M] \\
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Steven Vickers (2017). "Arithmetic universes and classifying toposes". In: *Cahiers de topologie et géométrie différentielle catégorique* vol.58.4, pp. 213–248. URL: http://cahierstgdc.com/wp-content/uploads/2018/01/Vickers-58-34.pdf

Chevalley fibrations

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- Suppose $\mathbb{K}$ is a 2-category with finite (strict) PIE-limits, in other words those reducible to Products, Inserters and Equifiers.
- This is enough to guarantee existence of all strict comma objects.

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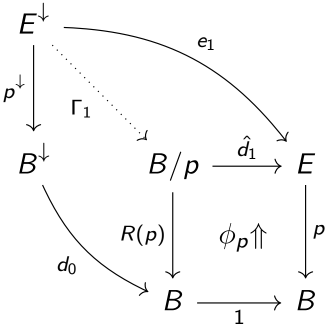
- Suppose B is an object of $\mathbb{K}$, and p is a 0-cell in the strict slice 2-category $\mathbb{K}/B$. p is a **Chevalley fibration** if the 1-cell Γ_1 has a right adjoint Λ_1 with counit an identity in the 2-category $\mathbb{K}/B$.



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- (Street, 1974) characterizes Chevalley fibrations as pseudo-algebras of a slicing KZ 2-monads on 2-categories in Ross Street (1974). "Fibrations and Yoneda's lemma in a 2-category". In: *Lecture Notes in Math., Springer, Berlin* vol.420, pp. 104–133.

Fibrational extension of contexts

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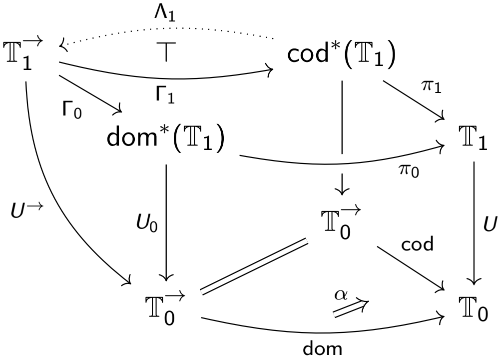
- Any extension map of contexts $U\colon \mathbb{T}_1 \to \mathbb{T}_0$ in the 2-category $\mathfrak{Con}$ is (strictly) carrable.
- Using this fact, and since comma objects exists in $\mathfrak{Con}$, we reformulate the notion of Chevalley fibration in $\mathfrak{Con}$.

Fibrational extension of contexts

- An extension map is called **fibrational** if Γ_1 has a right adjoint with identity counit.



Main theorem

THEOREM

If $U : \mathbb{T}_1 \to \mathbb{T}_0$ is a (op)fibrational extension of contexts, and M is any model of $\mathbb{T}_0$ in an elementary topos $\mathcal{S}$, then $p : \mathcal{S}[\mathbb{T}_1/M] \to \mathcal{S}$ is an (op)fibration of toposes.

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Hazratpour Sina and Steve Vickers (2018). "Fibrations of contexts beget fibrations of toposes". In: URL: sinhp.github.io/publication/fibrations-context-topos

Local homeomorphism of toposes as opfibration

- For $\mathcal{S}$ a bounded $\mathcal{S}_0$ topos, and $\mathbb{T}_0 = \mathbb{O}$ and $\mathbb{T}_1$ the extended context of $\mathbb{T}_0$ with a fresh edge from terminal to the unique node of $\mathbb{T}_0$.

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- And a bipullback of toposes

$$\begin{array}{ccc} \mathcal{S}/M \simeq \mathcal{S}[\mathbb{T}_1/M] & \longrightarrow & \mathcal{S}_0[X,x] = \mathcal{S}_0[X][\mathbb{T}_1/X] \\ {\scriptstyle M^*p}\downarrow & & \downarrow{\scriptstyle p} \\ \mathcal{S} & \underset{M}{\longrightarrow} & \mathcal{S}_0[X] \end{array}$$

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- $M^* p$ is a fibration of toposes.

Spectrum of Boolean algebras

- For $\mathcal{S}$ a bounded $\mathcal{S}_0$ topos, and $\mathbb{T}_0$ = context of Boolean algebras and $\mathbb{T}_1$ the extended context of Boolean algebra with a prime filter
- We get a context extension map $\mathbb{T}_1 \to \mathbb{T}_0$ which is a fibration.
- And a bipullback of toposes

$$\begin{array}{ccc} Spec(B) & \longrightarrow & \mathcal{S}[\mathbb{T}_1/B] \\ {\scriptstyle M^*p}\downarrow & & \downarrow{\scriptstyle p} \\ 1 & \xrightarrow[B]{} & \mathcal{S} \end{array}$$

- The points of $\mathcal{S}[\mathbb{T}_1/B]$ are pairs (B, F) where F is an internal prime filter of B in topos $\mathcal{S}$. "every fibrewise Stone bundle is a fibration."

Other examples

- Internal Algebraic dcpos as opfibrations
- Spectral spaces as fibrations
- SFP domains as bifibrations
- Internal groups equipped with an action as fibrations
- Intenral categories equipped with a torsor as opfibrations
- Internal modules as bifibrations
- Bag domains as opfibrations
- . . .

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End!

Thank you for your attention!