# On the Fibrations Underlying Optimization and Elimination

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**Abstract**

*As of July 25, 2019:* The theory of fibrations and fibered categories appears to be a natural place to discuss the theory of various optimization and elimination problems, including resolution in logic, linear and non-linear quantifier elimination, polytope projection, lattice optimization over various spaces, etc. These notes aim to investigate that claim and furthermore attempts to determine any and all structural similarities between the various cases.

# Contents

# Notation Proposals

- $\mathsf{Aff}$ the category of affine spaces (?) and affine maps between them
- $\mathsf{Vect}$ the category of vector spaces and the linear maps between them
- $\mathsf{Poly}$ the category of polyhedra and the affine maps between them
- $\mathsf{Cone}$ the category of cones and the linear maps between them

# 1 Introduction

Below is a provisional list of various notions of "elimination":

- The **resolution rule** of propositional (and also first order) logics. Two clauses containing a complementary literals (e.g. variable $c$ in one and its negation $\neg c$ in the other) entails a clause with the complementary literals eliminated (see *Ground resolvents and Ground resolution* in [robinson1965machine Rob+65]):[1]

  $$\frac{a_1 \vee a_2 \vee \cdots \vee c, \quad b_1 \vee b_2 \vee \cdots \vee \neg c}{a_1 \vee a_2 \vee \cdots \vee b_1 \vee b_2 \vee \cdots}$$

  Equivalently,

  $$\frac{(\neg a_1 \wedge \neg a_2 \wedge \cdots) \to c, \quad c \to (b_1 \vee b_2 \vee \cdots)}{(\neg a_1 \wedge \neg a_2 \wedge \cdots) \to (b_1 \vee b_2 \vee \cdots)}$$

  This generalizes to arbitrary conjunctions of literals which may or may not reference $c$ or $\neg c$.

- The incremental step of **Fourier-Motzkin elimination** [ziegler2012lectures Zie12] for systems of linear inequalities. Given

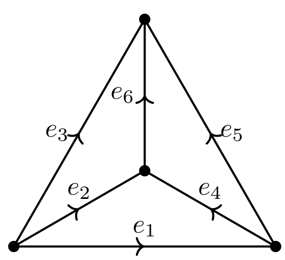
  $$a_0 + a_1x_1 + a_2x_2 + \cdots + a_nx_n \geq 0, \quad b_0 + b_1x_1 + b_2x_2 + \cdots + b_nx_n \geq 0$$

  with $a_1 > 0$ and $b_1 < 0$, then

  $$\left(\frac{a_0}{a_1} + \frac{a_2}{a_1}x_2 + \cdots + \frac{a_n}{a_1}x_n\right) - \left(\frac{b_0}{b_1} + \frac{b_2}{b_1}x_2 + \cdots + \frac{b_n}{b_1}x_n\right) \geq 0$$

  This generalizes to arbitrary systems of linear inequalities over a set of variables containing $x_1$.

- The **elimination axiom of oriented matroids** [bjorner1999oriented Bjo+99, circuit axiom (C3)]. Given two citcuits $X_0 = (X_0^+, X_0^-), X_1 = (X_1^+, X_1^-)$ (with $X_0 \neq -X_1$), and an element $e \in X_0^+ \cap X_1^-$ which is positively oriented in one circuit and negatively oriented in the other, then the circuits can be "glued" along $e$ producing a new circuit $X = (X^+, X^-)$ satisfying $X^+ \subseteq X_0^+ \cup X_1^+ \setminus \{e\}$ and $X^- \subseteq X_0^- \cup X_1^- \setminus \{e\}$ (i.e. it at least eliminates $e$). For example, the oriented matroid generated by the cycles of the following graph

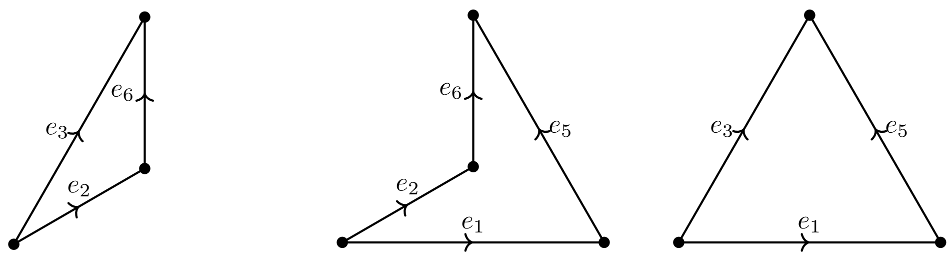


(1)

[1] Reference https://en.wikipedia.org/wiki/Resolution_(logic).

satisfies the elimination axiom. The following example eliminates $e_2$ (an indirectly eliminates $e_6$):

$$X_0 = (\{e_2, e_6\}, \{e_3\}) \qquad X_1 = (\{e_1, e_5\}, \{e_2, e_6\}) \qquad X = (\{e_1, e_5\}, \{e_3\})$$




(2)

**TC:** Generally, this "elimination" of $n-1$ surfaces by gluing together $n$-dimensional surfaces reminds me of the analogous idea in the homology theory of polyhedra; assign to each $n$-dimensional face the sum of the $n-1$ faces *incidence* to it (its boundary) as a formal sum in the free abelian group of all $n-1$ faces modulo 2 (the modulo 2 carries out the unoriented elimination).

# 2 Category Theory Terminology

The following unordered list of categorical concepts are anticipated to be utilized:

- adjunctions
- fibered categories
- cleavages
- pseudo functors (and if cleavages are splitting, functors)
- Beck-Chevalley condition
- Frobenius reciprocity (and functors of monoidal categories)

**Tobias:** Cleavages are not really important because for any two different choices of cleavage, the resulting pullback functors are naturally isomorphic. So cleavages are just a technical tool relevant for proving the equivalence between fibred cats and pseudofunctors, but not relevant in practice

**TC:** The above comment makes sense. Overall there are isomorphisms lurking behind every corner: first, there are natural isomorphisms present when considering the equivalence between pseudo-functors and "cleavaged" fibered categories, and second, whenever the cartesian arrows are indeed pullbacks, they are unique up to unique isomorphism and thus entire cleavages are unique up to unique isomorphisms. For a discussion see [Vis04] at the end of Section 3.1.3. starting on page 50.

## 2.1 Cartesian Arrows

**Definition 2.1.** Let $P : \mathcal{E} \to \mathcal{B}$ be a functor between categories $\mathcal{E}$ and $\mathcal{B}$. An arrow $\phi : \alpha \to \beta$ of $\mathcal{E}$ is *cartesian* with respect to $P$ (sometimes $P$-*cartesian*) if for every arrow $\psi : \gamma \to \beta$ sharing a codomain with $\phi$, and for every arrow $g : P(\gamma) \to P(\alpha)$ in $\mathcal{B}$ satisfying $g \circ P(\phi) = P(\psi)$, there exists a unique arrow $\theta : \gamma \to \alpha$

in $\mathcal{E}$ satisfying $\phi \circ \theta = \psi$ and $P(\theta) = g$.

$$\begin{tikzcd}
\gamma \arrow[dr, dashed, "\exists ! \theta"'] \arrow[drr, bend left, "\forall \psi"] \arrow[dd, mapsto] & & \\
& \alpha \arrow[r, "\phi"'] \arrow[dd, mapsto] & \beta \arrow[dd, mapsto] \\
P(\gamma) \arrow[dr, "\forall g"'] \arrow[drr, bend left, "P(\psi)"] & & \\
& P(\alpha) \arrow[r, "P(\phi)"'] & P(\beta)
\end{tikzcd} \tag{3}$$

**Corollary 2.0.1.** *A cartesian morphism $\phi : \alpha \to \beta$ in $\mathcal{E}$ with respect to a functor $P : \mathcal{E} \to \mathcal{B}$ establishes an isomorphism of categories [Lur09, Section 2.4.1]*[2]

$$\mathcal{E}/\phi \cong \mathcal{E}/\beta \times_{\mathcal{B}/P(\beta)} \mathcal{B}/P(\phi) \tag{4}$$

*where $\mathcal{E}/\beta \times_{\mathcal{B}/P(\beta)} \mathcal{B}/P(\phi)$ is the pullback of functors.*

$$\begin{tikzcd}
\mathcal{E}/\phi \arrow[dr, dashed, leftrightarrow, "\cong"] \arrow[drr, bend left, "P/\phi"] \arrow[ddr, bend right, "\mathrm{cod}"'] & & \\
& \mathcal{E}/\beta \times_{\mathcal{B}/P(\beta)} \mathcal{B}/P(\phi) \arrow[r] \arrow[d] \arrow[dr, phantom, "\lrcorner", very near start] & \mathcal{B}/P(\phi) \arrow[d, "\mathrm{cod}"] \\
& \mathcal{E}/\beta \arrow[r, "P/\beta"] & \mathcal{B}/P(\beta)
\end{tikzcd} \tag{5}$$

The pullback category $\mathcal{E}/\beta \times_{\mathcal{B}/P(\beta)} \mathcal{B}/P(\phi)$ has morphisms associated with diagrams of $\mathcal{B}$ with the following format:

$$\begin{tikzcd}
& P(\gamma) \arrow[d, "P(\chi)"] \arrow[ddl, bend right, "f"'] \arrow[ddr, bend left, "P(\omega)"] & \\
& P(\delta) \arrow[dl, "g"'] \arrow[dr, "P(\psi)"] & \\
P(\alpha) \arrow[rr, "P(\phi)"] & & P(\beta)
\end{tikzcd} \tag{6}$$

eq:pullback_

Evidently, if $\phi : \alpha \to \beta$ is cartesian, then there exists unique morphisms $\zeta : \gamma \to \alpha$ and $\eta : \delta \to \alpha$ such that $P(\zeta) = f$ and $P(\eta) = g$ and the following diagram of $\mathcal{E}$ commutes:

$$\begin{tikzcd}
& \gamma \arrow[d, "\chi"] \arrow[ddl, bend right, "\zeta"'] \arrow[ddr, bend left, "\omega"] & \\
& \delta \arrow[dl, "\eta"'] \arrow[dr, "\psi"] & \\
\alpha \arrow[rr, "\phi"] & & \beta
\end{tikzcd} \tag{7}$$

eq:cartesian_

Intuitively, if $\phi$ is cartesian, then in order to determine the category $\mathcal{E}/\phi$ over $\phi$, it is sufficient to specify $\mathcal{E}/\beta \times_{\mathcal{B}/P(\beta)} \mathcal{B}/P(\phi)$.

[2] This formulation is also discussed here: https://ncatlab.org/nlab/show/Cartesian+morphism#CartInOrdCatReformulation.

## 2.2 Fibrations, Fibered Categories, and Cleavages

**Definition 2.2.** A *fibered category over* $\mathcal{B}$ is a category $\mathcal{E}$ associated to the domain of a functor, referred to as the *fibration*, $P : \mathcal{E} \to \mathcal{B}$ with the property that for every morphism $f : a \to b$ of $\mathcal{B}$ and object $\beta$ such that $P(\beta) = b$, there exists a cartesian arrow $\phi : \alpha \to \beta$ with $P(\phi) = f$.

**Lemma 2.1.** *A fibration $P : \mathcal{E} \to \mathcal{B}$ is a faithful functor if and only if its fibers are thin.*

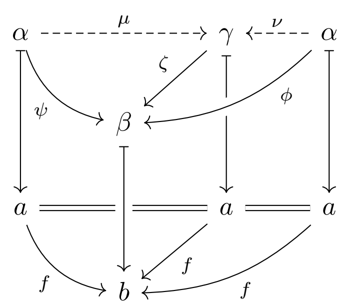
*Proof.* Recall that if $P : \mathcal{E} \to \mathcal{B}$ is a faithful functor, then by definition every pair of parallel arrows $\phi, \psi : \alpha \to \beta$ in $\mathcal{E}$ satisfies

$$P(\phi) = P(\psi) : P(\alpha) \to P(\beta) \implies \phi = \psi. \tag{8}$$

eq:faithfulne

$\implies$ : Assuming $P : \mathcal{E} \to \mathcal{B}$ is faithful functor, consider an arbitrary pair of parallel arrows $\phi, \psi : \alpha \to \beta$ in an arbitrary fiber $\mathcal{E}_x$ over $x$; i.e. $P(\phi) = P(\psi) = \mathrm{id}_x$. In such cases, faithfulness of $P$ (Eq. 8) guarantees that $\phi = \psi$ and thus $\mathcal{E}_x$ is a thin category. eq:faithfulness

$\impliedby$ : If the fiber $\mathcal{E}_x$ for every object $x$ in $\mathcal{B}$ is a thin category, then clearly $P : \mathcal{E} \to \mathcal{B}$ *must* be faithful when restricted to an individual fiber. The non-trivial case is to consider an arbitrary pair of parallel morphisms $\phi, \psi : \alpha \to \beta$ not belonging to any fibers of $\mathcal{E}$. Denote $a := P(\alpha)$ and $b := P(\beta)$ and suppose $f := P(\phi) = P(\psi) : a \to b$. Then, because $\mathcal{E}$ is a fibered category, there exists a cartesian arrow $\zeta : \gamma \to \beta$, such that $P(\zeta) = f$ (note that $a = P(\alpha) = P(\gamma)$ but $\gamma$ is not necessarily equal to $\alpha$). Since $\zeta$ is a cartesian arrow, there exists a unique arrows $\mu, \nu : \alpha \to \gamma$ completing the top edges of the following diagram:

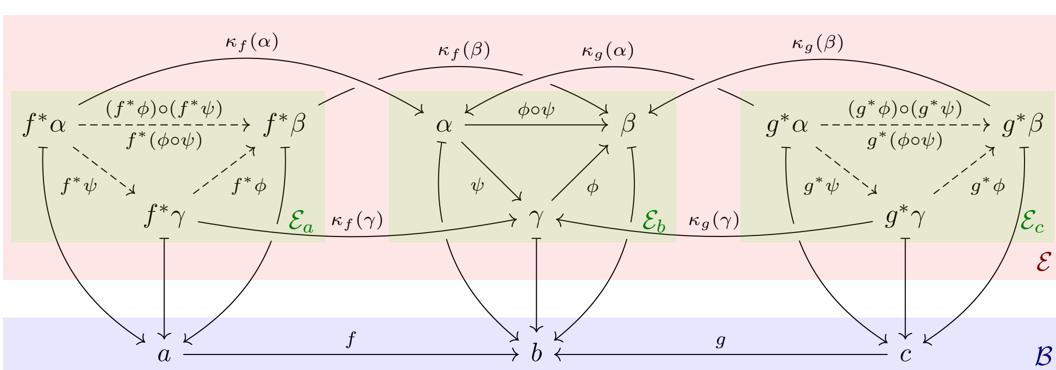


. (9)

However, $P(\nu) = \mathrm{id}_a = P(\mu)$ and therefore $\mu$ and $\nu$ are parallel arrows in the fiber $\mathcal{E}_a$ and therefore $\mu = \nu$ because $\mathcal{E}_a$ is assumed thin. Therefore, $\psi = \zeta \circ \mu = \zeta \circ \nu = \phi$ and thus $P$ is a faithful functor. $\square$

**Definition 2.3.** A *cleavage* for a fibration $P : \mathcal{E} \to \mathcal{B}$ is an assignment to each morphism $f : a \to b$ of $\mathcal{B}$ and object $\beta$ in $\mathcal{E}_b$ (i.e. $P(\beta) = b$), a unique cartesian morphism $\kappa_f(B)$ of $\mathcal{E}$ such that $P(\kappa_f(B)) = f$.

Given a cleavage for a fibration, the cartesianness of morphisms within a cleavage permits one to establish functors between the fibers of the fibration. This concept is visualized in the following figure:



(10)

## 2.3 Pseudo-Functors, Splitting Cleavages

Pages 47-48 of vistoli2004notes [Vis04] explicate the notions of pseudo-functors and their equivalence to fibrations with cleavages. Morover if the cleavage is splitting, the induced pseudo-functor is in fact a functor.

## 2.4 Nearby Fibrations: Opfibrations and $*$-fibrations

Given a functor $P : \mathcal{E} \to \mathcal{B}$, it can be considered as a fibration in many different ways. For example, if $P^{\mathrm{op}} : \mathcal{E}^{\mathrm{op}} \to \mathcal{B}^{\mathrm{op}}$ is a fibration, then $P$ is said to be an *opfibration*.

## 2.5 Hom-Functors

For a locally small category $\mathcal{C}$, the hom-functor of $\mathcal{C}$ is a functor $\mathrm{Hom}_{\mathcal{C}} : \mathcal{C}^{\mathrm{op}} \times \mathcal{C} \to \mathsf{Set}$ constructed in the following manner. Given objects $a, b, c, \ldots \in \mathcal{C}_0$ of $\mathcal{C}$, the hom-functor $\mathrm{Hom}_{\mathcal{C}}$ maps a pair of objects $(a, b) \in (\mathcal{C}^{\mathrm{op}} \times \mathcal{C})_0 = \mathcal{C}_0 \times \mathcal{C}_0 = \mathcal{C}_0^2$ into the set[3] of morphisms $\mathcal{C}_1$ of $\mathcal{C}$ with source $a$ and target $b$. Therefore, $\mathrm{Hom}_{\mathcal{C}}(a, b)$ is the set of morphisms in $\mathcal{C}$ of type $a \to b$. Given morphisms $g^{\mathrm{op}} \in \mathrm{Hom}_{\mathcal{C}^{\mathrm{op}}}(a, c)$ and $h \in \mathrm{Hom}_{\mathcal{C}}(b, d)$, the hom-functor $\mathrm{Hom}_{\mathcal{C}}$ constructs a function

$$\mathrm{Hom}_{\mathcal{C}}(g^{\mathrm{op}}, h) : \mathrm{Hom}_{\mathcal{C}}(a, b) \to \mathrm{Hom}_{\mathcal{C}}(c, d)$$

which takes a morphism $f : a \to b \in \mathrm{Hom}_{\mathcal{C}}(a, b)$ and produces the morphism $h \circ f \circ g : c \to d \in \mathrm{Hom}_{\mathcal{C}}(c, d)$. Graphically,

$$\mathrm{Hom}_{\mathcal{C}}(g^{\mathrm{op}}, h)\left( a \xrightarrow{f} b \right) = \; c \xrightarrow{g} a \xrightarrow{f} b \xrightarrow{h} d$$

## 2.6 Adjoint Functors

Given two categories $\mathscr{C}$ and $\mathscr{D}$, a pair of functors $L : \mathscr{C} \to \mathscr{D}, R : \mathscr{D} \to \mathscr{C}$ are called an *adjoint pair*, denoted $L \dashv R$ or

$$\begin{tikzcd} \mathcal{C} \arrow[r, bend left, "L"] \arrow[r, phantom, "\perp"] & \mathcal{D} \arrow[l, bend left, "R"] \end{tikzcd}$$

if there exists a natural isomorphism $\alpha$ between the following pair of hom-functors of type $\mathscr{C}^{\mathrm{op}} \times \mathscr{D} \to \mathsf{Set}$:

$$\mathrm{Hom}_{\mathscr{D}}(L^{\mathrm{op}}(-), -) \overset{\alpha}{\simeq} \mathrm{Hom}_{\mathscr{C}}(-, R(-))$$

This relationship can be depicted graphically as 2-cell (and its inverse) in $\mathsf{Cat}$,

$$\begin{tikzcd} \mathcal{C}^{\mathrm{op}} \times \mathcal{D} \arrow[r, "I_{\mathcal{C}^{\mathrm{op}}} \times R"] \arrow[d, "L^{\mathrm{op}} \times I_{\mathcal{D}}"'] \arrow[dr, phantom, "\overset{\alpha}{\Rightarrow} \; \overset{\Leftarrow}{\alpha^{-1}}"] & \mathcal{C}^{\mathrm{op}} \times \mathcal{C} \arrow[d, "\mathrm{Hom}_{\mathcal{C}}"] \\ \mathcal{D}^{\mathrm{op}} \times \mathcal{D} \arrow[r, "\mathrm{Hom}_{\mathcal{D}}"] & \mathsf{Set} \end{tikzcd}$$

[3]The collection of morphisms of type $a \to b$ forms a set because $\mathcal{C}$ is locally small.

Concretely, the naturality of $\alpha$ means that for every morphism $(f^{\mathrm{op}} : b \to a, g : c \to d) \in (\mathcal{C}^{\mathrm{op}} \times \mathcal{D})_1$ the components $\alpha_{(b,c)}$ and $\alpha_{(a,d)}$ of $\alpha$ make the following square commute:

$$\begin{tikzcd}
\mathrm{Hom}_{\mathcal{D}}(L^{\mathrm{op}}(b), c) \arrow[r, "\mathrm{Hom}_{\mathcal{D}}(L^{\mathrm{op}}(f^{\mathrm{op}}), g)"] \arrow[d, "\alpha_{(b,c)}"'] & \mathrm{Hom}_{\mathcal{D}}(L^{\mathrm{op}}(a), d) \arrow[d, "\alpha_{(a,d)}"] \\
\mathrm{Hom}_{\mathcal{C}}(b, R(c)) \arrow[r, "\mathrm{Hom}_{\mathcal{C}}(f^{\mathrm{op}}, R(g))"] & \mathrm{Hom}_{\mathcal{C}}(a, R(d))
\end{tikzcd}$$

## 2.7 Beck-Chevalley Conditions

The Beck-Chevalley Conditions are conditions that may or may not be satisfied by a quadruplet of functors $F, H, G, K$ which form a natural isomorphism $\alpha : KF \Rightarrow HG$ square:

$$\begin{tikzcd}
\mathcal{A} \arrow[r, "F"] \arrow[d, "G"'] \arrow[dr, phantom, "\swArrow\alpha"] & \mathcal{B} \arrow[d, "K"] \\
\mathcal{C} \arrow[r, "H"'] & \mathcal{D}
\end{tikzcd}$$

To define the *left* Beck-Chevalley condition, one needs functors $F_L : \mathcal{B} \to \mathcal{A}$ and $H_L : \mathcal{D} \to \mathcal{A}$ which are respectively left adjoint functors to $F$ and $H$,

$$\begin{tikzcd}
\mathcal{A} \arrow[r, bend right, "F"'] \arrow[r, phantom, "\perp"] & \mathcal{B} \arrow[l, bend right, "F_L"']
\end{tikzcd}, \qquad
\begin{tikzcd}
\mathcal{C} \arrow[r, bend right, "H"'] \arrow[r, phantom, "\perp"] & \mathcal{D} \arrow[l, bend right, "H_L"']
\end{tikzcd}.$$

Using these left adjoint functors, it becomes possible to construct a natural transformation $\beta : KH_L \Rightarrow GF_L$ from $\alpha$[4]. Graphically, $\beta$ can be identified as the outer cell of the following diagram:

$$\begin{tikzcd}
\mathcal{A} \arrow[r, bend right, "F"'] \arrow[r, phantom, "\perp"] \arrow[d, "G"'] \arrow[dr, phantom, "\swArrow\alpha"] & \mathcal{B} \arrow[l, bend right, "F_L"'] \arrow[d, "K"] \\
\mathcal{C} \arrow[r, bend left, "H"] \arrow[r, phantom, "\top"] & \mathcal{D} \arrow[l, bend left, "H_L"]
\end{tikzcd}, \quad \text{i.e.} \quad
\begin{tikzcd}
\mathcal{A} \arrow[d, "G"'] & \mathcal{B} \arrow[l, "F_L"'] \arrow[d, "K"] \arrow[dl, phantom, "\nwArrow\beta"] \\
\mathcal{C} & \mathcal{D} \arrow[l, "H_L"]
\end{tikzcd}.$$

Although the natural transformation $\alpha$ is assumed to be a natural isomorphism, the natural transformation $\beta$ need not be; if $\beta$ happens to be a natural isomorphism, then we say that the original square satisfies the *left* Beck-Chevalley condition[5]. The *right* Beck-Chevalley condition is defined analogously with functors $F_R, H_R$ which are respectively right adjoints $F \dashv F_R$ and $H \dashv H_R$.

[4] The natural transformations $\alpha$ and $\beta$ are known as *mates* or *conjugates*.

[5] Are the left adjoints $F_L, H_L$ unique? If not, it might be better to say the original square satifies the left Beck-Chevalley condition with respect to $F_L, H_L$.

## 2.8 Slice and Coslice Categories

Given a category $\mathcal{C}$ and an object $c \in \mathcal{C}_0$ of $\mathcal{C}$, the *slice category* (or *over category*) $\mathcal{C}/c$ is the "stuff in $\mathcal{C}$ that is on top of $c$". Specifically, the objects of $\mathcal{C}/c$ are all the morphisms $f \in \mathcal{C}_1$ from $\mathcal{C}$ whose codomain is $\mathrm{cod}(f) = c$ (alternatively you could write $(\mathcal{C}/c)_0 = \mathrm{Hom}_{\mathcal{C}}(-, c)$). A morphism of $\mathcal{C}/c$ between objects $f : a \to c, g : b \to c \in (\mathcal{C}/c)_0$ is a commuting triangle completed by a third morphism $h : a \to b \in \mathcal{C}_1$:

$$\begin{tikzcd} a \arrow[rr, "h"] \arrow[dr, "g"'] & & b \arrow[dl, "f"] \\ & c & \end{tikzcd}$$

Composition of morphisms in $\mathcal{C}/c$ is induced by the composition of morphisms in $\mathcal{C}$:

$$\left(\begin{tikzcd} y \arrow[rr, "n"] \arrow[dr, "f"'] & & z \arrow[dl, "h"] \\ & c & \end{tikzcd}\right) \circ_{\mathcal{C}/c} \left(\begin{tikzcd} x \arrow[rr, "m"] \arrow[dr, "g"'] & & y \arrow[dl, "f"] \\ & c & \end{tikzcd}\right) = \begin{tikzcd} x \arrow[r, "m"] \arrow[dr, "g"'] & y \arrow[r, "n"] \arrow[d, "f"] & z \arrow[dl, "h"] \\ & c & \end{tikzcd}$$

The assignment of an overcategory $\mathcal{C}/c$ to each object $c$ can be extended to a *slice functor* $\mathcal{C}/(-) : \mathcal{C} \to \mathbf{Cat}$ in the following sense. For objects $c \in \mathcal{C}_0$, the slice functor takes $c$ to the slice category $\mathcal{C}/c$; for morphisms $f : a \to b \in \mathcal{C}_1$, the slice functor takes $f$ to the functor $\mathcal{C}/f : \mathcal{C}/a \to \mathcal{C}/b$ defined graphically; for every morphism of $\mathcal{C}/a$ (commuting triangle in $\mathcal{C}$ over $a$), contruct the morphism of $\mathcal{C}/b$ (commuting triangle in $\mathcal{C}$ over $b$) as follows:

$$\begin{tikzcd} l \arrow[rr, "m"] \arrow[dr, "x"'] \arrow[ddr, bend right=60, "f \circ_{\mathcal{C}} x"'] & & r \arrow[dl, "x'"] \arrow[ddl, bend left=60, "f \circ_{\mathcal{C}} x'"] \\ & a \arrow[d, "f"] & \\ & b & \end{tikzcd}$$

where the inner triangle is a morphism of $\mathcal{C}/a$ and the outer triangle is a morphism of $\mathcal{C}/b$ given by the functor $\mathcal{C}/f$.

Given a category $\mathcal{C}$ and an object $c \in \mathcal{C}_0$ of $\mathcal{C}$ the *coslice category* (or *under category*) $c/\mathcal{C}$ is the "stuff in $\mathcal{C}$ that is underneath $c$". Specifically, the objects of $c/\mathcal{C}$ are all the morphisms $f \in \mathcal{C}_1$ from $\mathcal{C}$ whose domain is $\mathrm{dom}(f) = c$ (alternatively you could write $(c/\mathcal{C})_0 = \mathrm{Hom}_{\mathcal{C}}(c, -)$). A morphism of $c/\mathcal{C}$ between objects $f : c \to a, g : c \to b \in (c/\mathcal{C})_0$ is a commuting triangle completed by a third morphism $h : a \to b \in \mathcal{C}_1$:

$$\begin{tikzcd} & c \arrow[dl, "g"'] \arrow[dr, "f"] & \\ a \arrow[rr, "h"'] & & b \end{tikzcd}$$

Everything about coslice categories is defined as expected analogously to that of a slice categories.

**TODO:** determine how the details of the Grothendieck construction transform the slice (pseudo-)functor $\mathcal{C}/(-) : \mathcal{C} \to \mathbf{Cat}$ into the codomain fibration

## 2.9 Functors of Monoidal Categories

[TODO]

### 2.10 Frobenius Reciprocity

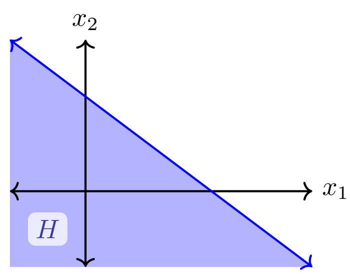
[TODO]

# 3 Case Studies of Interest

## 3.1 Polyhedra and Affine Maps

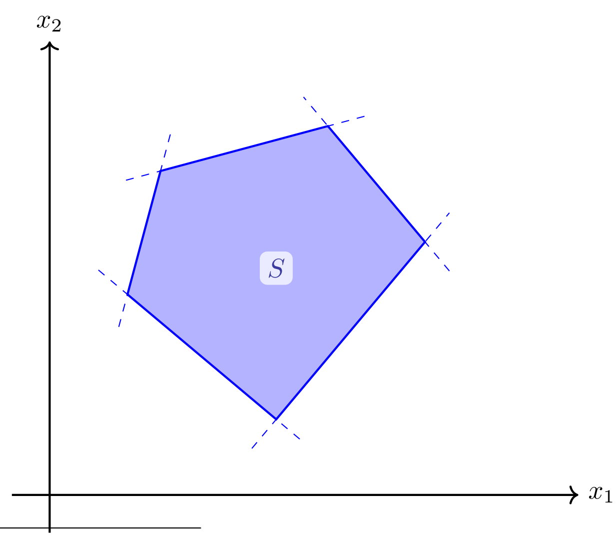
One of the primary motiviating examples for this project is the theory of *(finite) convex polyhedra* and the affine maps between them. Following Boyd and Vandenberghe [BV04], a *polyhedron*[6,7] $P$ is the intersection of a finite number of *halfspaces* of some ambient vector space $V \cong \mathbb{R}^n$. A *halfspace* $H \subseteq \mathbb{R}^n$ is a subset of a vector space (of dimension $n$) which is the solution set of a linear inequality constraint over canonical coordinates $x = (x_1, x_2, \ldots, x_n) \in \mathbb{R}^n$:

$$H = \{x \in V \mid a^\intercal x = \sum_{i=1}^{n} a_i x_i \geq b\} \tag{11}$$




As previously mentioned, a polyhedra is the intersection of finitely many halfspaces and therefore corresponds to

$$P = \{x \in V \mid \bigwedge_{j=1}^{k} (a_j^\intercal x \geq b_j)\} \tag{12}$$




[6] The term polytope will be reserved for the context of *bounded polyhedron*. Note that the opposite convention is sometimes used by other authors as pointed out by [BV04].

[7] Alternative and sometimes inequivalent definitions for "polyhedra" do exist; oftentimes, these alternative definitions accomodate more general notions of polyhedra, such as non-convex polyhedra. Understanding the relationship between these various definitions, and the proposal of new ones, is a mathematical endeavour which dates back to antiquity and continues today [Grü03; Lak15].

$$
\begin{tikzcd}
f^*(\mathbb{R}^k_+) \arrow[r, "f'"] \arrow[d, hook, "j"] \arrow[dr, phantom, "\lrcorner", very near start] & \mathbb{R}^k_+ \arrow[d, hook, "i"] \\
\mathbb{R}^n \arrow[r, "f"] & \mathbb{R}^k
\end{tikzcd}
\tag{13}
$$

eq:pullback_of_positive_orthant

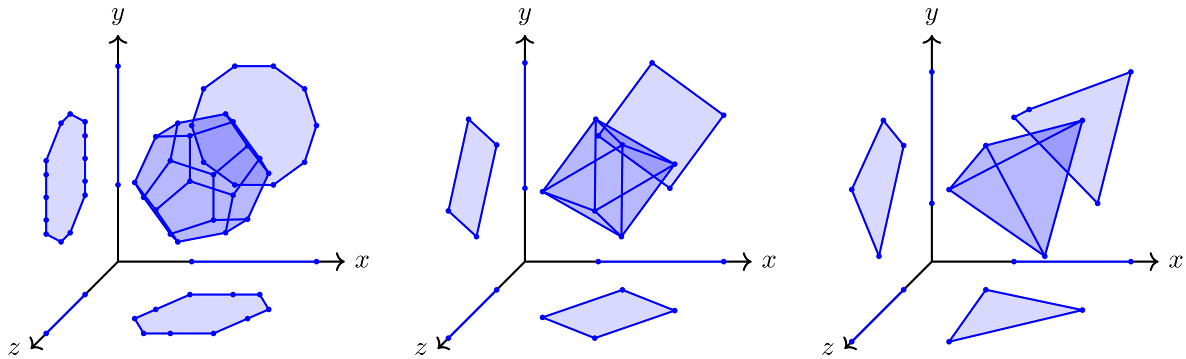
eq:pullback_of_positive_orthant

In Equation 13, the morphism $j$ is simply the inclusion of the polyhedra $f^*(\mathbb{R}^k_+)$ into its ambient vector space $\mathbb{R}^n$ and the morphism $f'$ is provided by the restriction of $f$ onto $f^*(\mathbb{R}^k_+)$.

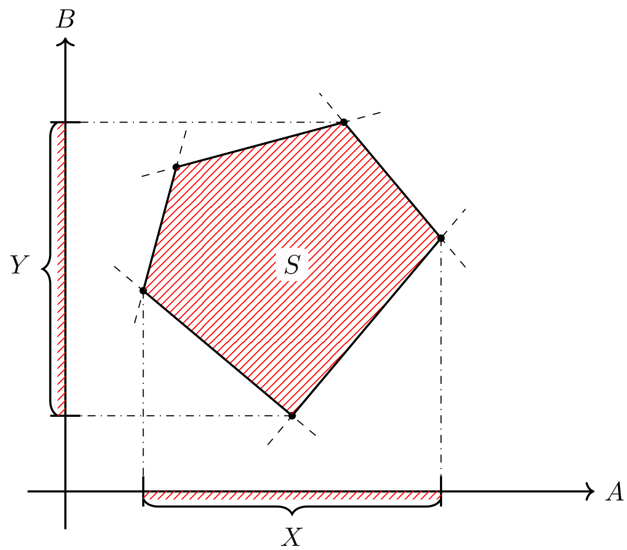
## 3.2 The Beck-Chevalley Condition for the Polyhedral Fibration

Consider a commuting square of affine maps between vector spaces in the base category of affine maps

**Definition 3.1.** The category Poly consists of polyhedra as objects and affine maps between them.




$$
\begin{tikzcd}
& \mathsf{Poly}_Y \arrow[dd, "\pi_{1,!}"] & & \mathsf{Poly}_{X\otimes Y} \arrow[ll, "\pi_{Y,!}"'] \arrow[dd, "\pi_{X,!}"] \\
\mathsf{Poly}_{Y\otimes Z} \arrow[ur, "\pi_{Y,!}"] \arrow[dd, "\pi_{Z,!}"] & & \mathsf{Poly}_{X\otimes Y\otimes Z} \arrow[ll, "\pi_{Y\otimes Z,!}"'] \arrow[ur, "\pi_{X\otimes Y,!}"] \arrow[dd, "\pi_{X\otimes Z,!}"] & \\
& \mathsf{Poly}_1 & & \mathsf{Poly}_X \arrow[ll, "\pi_{1,!}"'] \\
\mathsf{Poly}_Z \arrow[ur, "\pi_{1,!}"] & & \mathsf{Poly}_{X\otimes Z} \arrow[ll, "\pi_{Z,!}"'] \arrow[ur, "\pi_{X,!}"] &
\end{tikzcd}
\tag{14}
$$



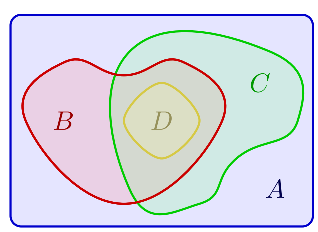

## 3.3 The Subobject Fibration

Given any category $\mathcal{B}$, and an object $X$ of $\mathcal{B}$, a *subobject* of $X$ is an isomorphism class of monomorphisms $f : Y \hookrightarrow X$; two monomorphisms $f : Y \hookrightarrow X, g : Z \hookrightarrow X$ with shared codomain $X$ are isomorphic if there exists an isomorphism $h : Y \xrightarrow{\sim} Z$ such that $f = g \circ h$. The individual monomorphisms of a subobject class can be equipped with a preorder relation $(f : Y \hookrightarrow Z) \leq (g : Z \hookrightarrow X)$ if there exists $k : Y \to Z$ such that $f = g \circ k$:

$$\begin{tikzcd} Y \arrow[rr, "k"] \arrow[dr, hook, "f"'] & & Z \arrow[dl, hook', "g"] \\ & X & \end{tikzcd} \tag{15}$$

Note that if such a $k : Y \to Z$ exists, then it is unique because it $g$ is a monomorpism; if $k' : Y \to Z$ satisfied $f = g \circ k'$ as well, then $g \circ k = g \circ k'$ which implies $k = k'$. Moreover, this preorder relation on the individual monomorphisms extends to a poset $\mathsf{Sub}_{\mathcal{B}}(X)$ between the subobjects. For example, if $\mathcal{B}$ is the category $\mathsf{Set}$, the subobjects of $X$ are subsets of $X$ and thus $\mathsf{Sub}_{\mathsf{Set}}(X) \cong \mathsf{P}(X)$. Even more concretely, if $X$ is the set $\mathbb{R}^2$, an exemplary diagram of $\mathsf{Sub}_{\mathsf{Set}}(\mathbb{R}^2)$ is

$$\begin{tikzcd} & A & \\ B \arrow[ur, hook, "\subseteq"] & & C \arrow[ul, hook', "\subseteq"'] \\ & D \arrow[ul, hook, "\subseteq"] \arrow[uu, hook, "\subseteq"] \arrow[ur, hook', "\subseteq"'] & \end{tikzcd}$$




If the category $\mathcal{B}$ has pullbacks, the posetal categories $\mathsf{Sub}_{\mathcal{B}}(X)$ for varying objects $X$ of $\mathcal{B}$ can be "stitched together" to form an enveloping category denoted $\mathsf{Sub}(\mathcal{B})$. The objects of $\mathsf{Sub}(\mathcal{B})$ are the objects of $\mathsf{Sub}_{\mathcal{B}}(X)$ for various $X$. The morphisms of $\mathsf{Sub}(\mathcal{B})$ are defined using the morphisms of $\mathcal{B}$. Given a equivalence class of monomorphisms $B = \{b_i : Z_i \hookrightarrow X\}_{i \in \mathcal{I}} \in \mathsf{Sub}_{\mathcal{B}}(X)$ with with shared codomain $X$, and morphism $f : Y \to X$ (not necessarily a monomorphism) with codmain $X$, the pullbacks $f^* b_i$ of $b_i$ along $f$ for each $i \in \mathcal{I}$ constitute an equivalence class of monomorphisms $f^*B \coloneqq \{f^*b_i : Y \times_X Z_i \hookrightarrow Y\}_{i \in \mathcal{I}} \in \mathsf{Sub}_{\mathcal{B}}(Y)$:[8,9]

$$\begin{tikzcd} Y \times_X Z_i \arrow[r, "b_i^* f"] \arrow[d, hook, "f^* b_i"'] \arrow[dr, phantom, "\lrcorner", very near start] & Z_i \arrow[d, hook, "b_i"] \\ Y \arrow[r, "f"] & X \end{tikzcd} \tag{16}$$

To every morphism $f : Y \to X$ of $\mathcal{B}$, and object $B \in \mathsf{Sub}_{\mathcal{B}}(X)$, denote $\kappa_f(B) : f^*B \to B$ where $f^*B \in \mathsf{Sub}_{\mathcal{B}}(Y)$. Finally, a morphism of $\mathsf{Sub}(\mathcal{B})$ between $A \in \mathsf{Sub}_{\mathcal{B}}(Y)$ and $B \in \mathsf{Sub}_{\mathcal{B}}(X)$ is the formal sequence $A \xrightarrow{\leq} f^*(B) \xrightarrow{\kappa_f(B)} B$. The projection functor $P_{\mathcal{B}} : \mathsf{Sub}(\mathcal{B}) \to \mathcal{B}$ defines the *subobject fibration*[10].

**TODO:** figure out the relationship between a subobject fibration and the codomain fibration via the notion of subterminal objects.

## 3.4 The Beck-Chevalley Condition for Any Subobject Fibration

Given any category $\mathcal{B}$ with all pullbacks, the functor $P_{\mathcal{B}} : \mathsf{Sub}_{\mathcal{B}} \to \mathcal{B}$ which sends subobjects $[\psi]$ to their shared codomains, constitutes a bifibration. In particular, given a morphism $f : a \to b$ of $\mathcal{B}$, there is an induced adjoint pair of functors between the subobject fibers:

$$\begin{tikzcd} \mathsf{Sub}_{\mathcal{B}}(a) \arrow[r, bend left, "f_!"] \arrow[r, phantom, "\perp"] & \mathsf{Sub}_{\mathcal{B}}(b) \arrow[l, bend left, "f^*"] \end{tikzcd} \tag{17}$$

Specfically, left adjoint functor $f_!$ acting on a subobject $[\psi] : \mathsf{Sub}_{\mathcal{B}}(a)$ (where $[\psi]$ is the equivalence class of monomorphisms into $a$ containing $\psi : a' \hookrightarrow a$) is given by post-composition $f_!([\psi]) = [f\psi] \in \mathsf{Sub}_{\mathcal{B}}(b)$ in $\mathcal{B}$. The right adjoint functor $f^*$ acting on a subobject $[\phi] \in \mathsf{Sub}_{\mathcal{B}}(b)$ is given by pullback of $a \xrightarrow{f} b \xleftarrow{\phi} b'$ in $\mathcal{B}$:

$$\begin{tikzcd} f^*b' \arrow[r] \arrow[d, hook, "f^*\phi"'] \arrow[dr, phantom, "\lrcorner", very near start] & b' \arrow[d, hook, "\phi"] \\ a \arrow[r, "f"'] & b \end{tikzcd} \tag{18}$$

Generally speaking, it is important to determine how diagrams in the base category $\mathcal{B}$ behave when lifted to the total category $\mathsf{Sub}_{\mathcal{B}}$ under the associated pseudo-functors. For example, given a pullback square in base category $\mathcal{B}$,

$$\begin{tikzcd} a \arrow[r, "f"] \arrow[d, "h"'] \arrow[dr, phantom, "\lrcorner", very near start] & b \arrow[d, "g"] \\ c \arrow[r, "k"'] & d \end{tikzcd} \tag{19}$$

There exists a natural isomorphism $\alpha$ between the functors $f^*g^*$ and $h^*k^*$:

$$\begin{tikzcd} \mathsf{Sub}_{\mathcal{B}}(a) & \mathsf{Sub}_{\mathcal{B}}(b) \arrow[l, "f"'] \\ \mathsf{Sub}_{\mathcal{B}}(c) \arrow[u, "h"] & \mathsf{Sub}_{\mathcal{B}}(d) \arrow[l, "k"] \arrow[u, "g"'] \arrow[ul, phantom, "\overset{\sim}{\Longleftarrow}\alpha"] \end{tikzcd} \tag{20}$$

[8]Evidently, this relies on the fact that pullbacks perserve monomorphisms; i.e. $b : Z \hookrightarrow X$ is a monomorphism, then the pullback $f^*b : Y \times_X Z \hookrightarrow Y$ is also.

[9]The isoмoprhisms connecting the monomorphisms of $f^*B$ are also given by pullback of the isomorphisms connecting the monomorphisms of $B$.

[10]Note that while the fibres $\mathsf{Sub}_{\mathcal{B}}(X)$ are thin, the total category $\mathsf{Sub}(\mathcal{B})$ is not necessarily thin.

The existence of components $\alpha_{[\psi]}$ for each subobject class containing the monomorphism $\psi : p \hookrightarrow d$ can be determined by examining the following diagram:

$$\begin{tikzcd}
 & & & f^*g^*p \arrow[dll, hook', bend right, "f^*g^*\psi"'] \arrow[d] \\
 & a \arrow[r, "f"] \arrow[d, "h"'] & b \arrow[d, "g"] & g^*p \arrow[l, hook', "g^*\psi"'] \arrow[dd] \\
 & c \arrow[r, "k"'] & d & \\
h^*k^*p \arrow[uur, hook, bend left, "h^*k^*\psi"] \arrow[r] & k^*p \arrow[u, hook, "k^*\psi"] \arrow[rr] & & p \arrow[ul, hook', "\psi"']
\end{tikzcd} \tag{21}$$

Using the composition of pullback squares, it is clear that *both* $f^*g^*p$ and $h^*k^*p$ are pullbacks of $a \xrightarrow{gf=kh} d \hookleftarrow{\psi} p$ and therefore, they are unique up to a unique isomorphism which will be denoted $\beta$. It is important to notice that this does not depend on $a$ being a pullback itself.

$$\begin{tikzcd}
h^*k^*p \arrow[rr, dashed, bend left, "\beta^{-1}"'] \arrow[d, hook, "h^*k^*\psi"'] \arrow[drr, bend left] & & f^*g^*p \arrow[ll, dashed, bend right, "\beta"'] \arrow[d] \arrow[dll, hook', bend right, "f^*g^*\psi"] \\
a \arrow[r, "gf=kh"'] & d & p \arrow[l, hook', "\psi"]
\end{tikzcd} \tag{22}$$

These isomorphisms actually establish that $h^*k^*\psi \simeq f^*g^*\psi$ and therefore they belong to the same equivalence class $[h^*k^*\psi] = [f^*g^*\psi]$ for each $\psi$. Therefore, it becomes clear that the natural isomorphism is indeed the identity natural transformation $\mathrm{id}_{f^*g^*} = \mathrm{id}_{h^*k^*} = \alpha : f^*g^* \to h^*k^*$.[11]

Alternatively, one can consider whether or not there exists natural transformations (or natural isomorphisms) of the form $\alpha : h_!f^* \to k^*g_!$. Remembering that the left adjoints $f_!$ are specified by post-composition $f_![\psi] \to [f\psi]$, this question can be answered by considering the following diagram:

$$\begin{tikzcd}
k^*gp \arrow[r, hook, "k^*g\psi"] \arrow[d] & c \arrow[d, "k"] & a \arrow[l, "h"'] \arrow[d, "f"] & f^*p \arrow[l, hook', "f^*\psi"] \arrow[d] \arrow[ll, bend right, "hf^*\psi"'] \\
p \arrow[r, "g\psi"] \arrow[rrr, equal, bend right] & d & b \arrow[l, "g"'] & p \arrow[l, hook', "\psi"']
\end{tikzcd} \tag{23}$$

Similarly, $k^*gp$ and $f^*p$ are *both* pullbacks of $p \xrightarrow{g\psi} d \hookleftarrow{k} c$ and therefore, we obtain an analogous statement: since $hf^*\psi \simeq k^*g\psi$, we have $[hf^*\psi] = [k^*g\psi]$ and therefore $h_!f^* = k^*g_!$. The key difference in this case is that this argument *does* rely on $a$ being the pullback of a pullback square.

In summary, the subobject fibration *satisfies* the Beck-Chevalley condition. Moreover, since none of the above argument relies on the fact that the objects of total category are represented by *monomorphisms* in the base, just that they correspond to *morpisms* in the base, it is clear that any codomain bifibration also satisfies the Beck-Chevalley condition.

## 3.5 The Category of Convex Cones and Linear Maps

Given any $\mathbb{R}$-vector space $V$, a *(closed) cone* $C \subseteq V$ is a subset of $V$ such that for any elements $c_1, c_2 \in C$ and for any positive coefficients $\gamma_1, \gamma_2 \geq 0$, $\gamma_1 c_1 + \gamma_2 c_2 \in C$. A finite cone $C \subseteq V$ admits a halfspace

[11] Ultimately, the reason for $\alpha = \mathrm{id}$ is due to considering $\mathsf{Sub}_{\mathcal{B}}(a)$, the *poset* of subobjects of $a$, instead of $\mathsf{Mono}_{\mathcal{B}}(a)$ the *preorder* of monomorphisms into $a$.

representation in terms a finite number of linear constraints:

$$C = \{x \in V \mid \bigwedge_{i=1}^{K} (a_i \cdot x \geq 0)\} \tag{24}$$

Alternatively, a $\mathsf{Cone}$ can be expressed in terms of the pullback of the positive orthant

$$\mathbb{R}^n_+ \coloneqq \{v \in \mathbb{R}^n \mid \forall i \in [n] : v_i \geq 0\} \tag{25}$$

by a linear transformation $f : V \to \mathbb{R}^n$ into $\mathbb{R}^n$.

$$\begin{tikzcd} f^*(\mathbb{R}^n_+) \arrow[r] \arrow[d, hook] \arrow[dr, phantom, "\lrcorner", very near start] & \mathbb{R}^n_+ \arrow[d, hook, "i_+"] \\ V \arrow[r, "f"] & \mathbb{R}^n \end{tikzcd} \tag{26}$$

$$f^*(\mathbb{R}^n_+) \cong \{v \in V \mid f(v) \in \mathbb{R}^n_+\} \tag{27}$$

Given a cone $f^*(\mathbb{R}^n_+) \subseteq V$ associated with a finite set of $n$ linear expressions $f : V \to \mathbb{R}^n$, and a linear transformation $g : V \to W$,

## 3.6 Subset Projection

A prototypical example wherein an adjoint triple

$$f_!, \exists_f \dashv f^*, f^{-1} \dashv f^!, \forall_f$$

arises is that of functions $f : X \to Y$ between sets $X$ and $Y$. The inverse image functor $f^* : \mathscr{P}Y \to \mathscr{P}X$ is defined on a subset $T \subseteq Y$

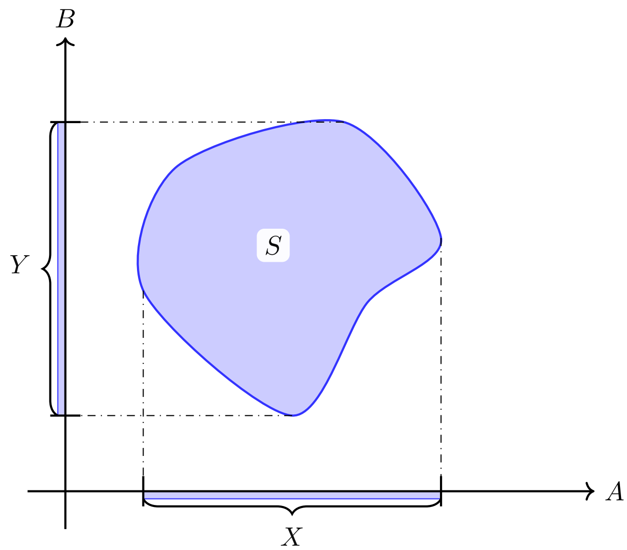
$$f^*(T) = \{x \in X : f(x) \in T\},$$

and is functorial in the sense that if $T \subseteq T' \subseteq Y$ then $f^*(T) \subseteq f^*(T') \subseteq f^*(T)$. The adjoint functors $\exists_f, \forall_f : \mathscr{P}X \to \mathscr{P}Y$ are defined on $S \subseteq X$ as

$$\exists_f(S) = \{y \in Y : \exists x \in f^*(y) : x \in S\}$$
$$\forall_f(S) = \{y \in Y : \forall x \in f^*(y) : x \in S\}$$

form an adjoint triple in the sense that $\exists_f \dashv f^* \dashv \forall_f$:

$$\exists_f \dashv f^* : \quad \exists_f(S) \subseteq T \iff S \subseteq f^*(T)$$
$$f^* \dashv \forall_f : \quad f^*(T) \subseteq R \iff T \subseteq \forall_f(R)$$

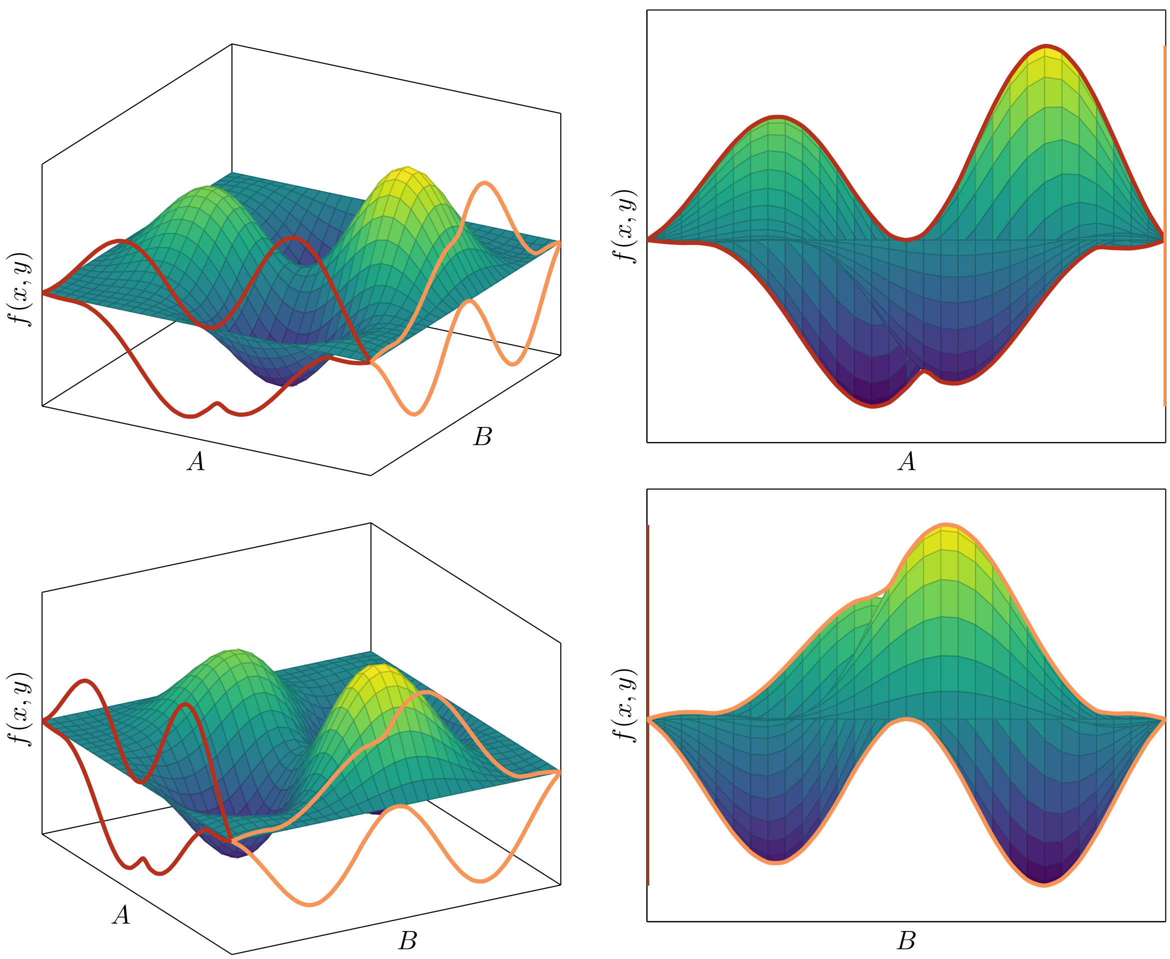


Consider a pair of sets $A$ and $B$ and a subset $S \subseteq A \times B$ of their cartesian product. The projection morphisms associated with $A \times B$ are $p : A \times B \to A$ and $q : A \times B \to B$. The projection of the subset $S$ onto $A$ is then the subset $X \subseteq A$ defined by:

$$X = \{a \in A \mid \exists s \in S, p(s) = a\}$$

$$S \subseteq p^*(X) \iff \exists_p(S) \subseteq X \tag{28}$$

### 3.7 Optimization of real-valued functions




## Comments on selected references

This section is temporary and reserved for recording comments toward various references.

- vistoli2004notes Vistoli [Vis04]
- street1974fibrations Street [Str74]
- koudenburg2018categorical Koudenburg [Kou18]
- brown2009algebraic Brown and Sivera [BS09]
- lurie2009higher Lurie [Lur09]

- Shulman [Shu08]
- Boyd and Vandenberghe [BV04]
- Bogart, Contois, and Gubeladze [BCG13]
- Gubeladze [Gub16]
- Fausk, Hu, and May [FHM03]
- Hofstra [Hof11]
- Ponto and Shulman [PS12]
- Mac Lane [Mac13]
- Ziegler [Zie12]
- Spectrahedron are interesting semi-algebaric sets. (https://www.youtube.com/watch?v=AevFRN5sx0U).

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