Projective classes as images of accessible functors

Friedrich Wehrung

Université de Caen
LMNO, CNRS UMR 6139
Département de Mathématiques
14032 Caen cedex
E-mail: friedrich.wehrung01@unicaen.fr
URL: http://wehrungf.users.lmno.cnrs.fr

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References

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- Let's suggest a stronger notion of intractability.

$\mathbf{v}$-structures

- Vocabulary: $\mathbf{v} = (\mathbf{v}_{\mathrm{ope}}, \mathbf{v}_{\mathrm{rel}}, \mathrm{ar})$ with $\mathbf{v}_{\mathrm{ope}} \cap \mathbf{v}_{\mathrm{rel}} = \varnothing$ and $\mathrm{ar}\colon \mathbf{v}_{\mathrm{ope}} \cup \mathbf{v}_{\mathrm{rel}} \to$ ordinals (usually) with $0 \notin \mathrm{ar}[\mathbf{v}_{\mathrm{rel}}]$.

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- Terms: closure of variables under all functions symbols.
- atomic formulas: $s = t$, for terms s and t, or $R(t_\xi \mid \xi \in \mathrm{ar}(R))$ where the t_ξ are terms and $R \in \mathbf{v}_{\mathrm{rel}}$.

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- Satisfaction $\boldsymbol{A} \models \mathrm{E}(\vec{a})$ defined as usual ($\boldsymbol{A}$ is a **v**-structure, $\mathrm{E} \in \mathscr{L}_{\infty\infty}(\mathbf{v})$, $\vec{a}$: free variables$\,(\mathrm{E}) \to A$).

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- $\mathscr{L}_{\kappa\lambda}$-elementary class:
  $\mathcal{C} = \mathbf{Mod}_{\mathbf{v}}(\mathrm{E}) \stackrel{\text{def}}{=} \{\boldsymbol{A} \in \mathbf{Str}(\mathbf{v}) \mid \boldsymbol{A} \models \mathrm{E}\}$ where E is an $\mathscr{L}_{\kappa\lambda}(\mathbf{v})$-sentence.

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- relatively projective over $\mathscr{L}_{\kappa\lambda}$ (abbrev. $\mathrm{RPC}(\mathscr{L}_{\kappa\lambda})$) if there are a unary predicate symbol U, a vocabulary $\mathbf{w} \supseteq \mathbf{v} \cup \{\mathrm{U}\}$, and a sentence $\mathsf{E} \in \mathscr{L}_{\kappa\lambda}(\mathbf{w})$ such that $\mathcal{C} = \{\mathrm{U}^{\boldsymbol{M}}\restriction_{\mathbf{v}} \mid \boldsymbol{M} \in \mathbf{Mod}_{\mathbf{w}}(\mathsf{E})\,,\ \mathrm{U}^{\boldsymbol{M}} \text{ closed under } \mathbf{v}_{\mathrm{ope}}\}$.

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- Hence $\mathrm{PC}(\mathscr{L}_{\kappa\lambda}) \subseteq \mathrm{RPC}(\mathscr{L}_{\kappa\lambda})$. Note that $\mathrm{PC}(\mathscr{L}_{\omega\omega}) \subsetneq \mathrm{RPC}(\mathscr{L}_{\omega\omega})$ (even on finite structures).

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Theorem (W 2021)

Let λ be an infinite cardinal. Then $\mathrm{PC}(\mathscr{L}_{\infty\lambda}) = \mathrm{RPC}(\mathscr{L}_{\infty\lambda})$ (in full generality; no restrictions on vocabularies). Moreover, if λ is singular, then $\mathrm{PC}(\mathscr{L}_{\infty\lambda}) = \mathrm{PC}(\mathscr{L}_{\infty\lambda^+})$.

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$$\bigvee\!\!\!\bigvee_{n<\omega}(\exists_{i<n}x_i)(\forall x)\bigvee\!\!\!\bigvee_{i<n}(x = x_i)\,.$$

Examples of "elementary" classes

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- Torsion-freeness (of a group) is $\mathscr{L}_{\omega_1\omega}$:

$$\bigwedge\!\!\!\!\bigwedge_{0<n<\omega}(\forall x)(x^n=1\Rightarrow x=1)\,.$$

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An example of RPC (that turns out to be PC)

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Elementary, projective

Tuuri's Interpolation Theorem

Karttunen's back-and-forth systems

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- Here $\mathbf{v} = (\underset{(2)}{\cdot}, \underset{(0)}{1})$, $\mathbf{w} = (\cdot, 1, \mathrm{U})$ for a unary predicate U, the required E states that the given $\mathbf{w}$-structure is a group (so "$\mathrm{U}^{\boldsymbol{G}}$ is $\mathbf{v}$-closed in $\boldsymbol{G}$" means that U interprets a submonoid of $\boldsymbol{G}$).

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- By Mal′cev's work, $\mathcal{C} = \{\boldsymbol{M} \mid (\forall n < \omega)(\boldsymbol{M} \models \mathsf{E}_n)\}$ for an effectively constructed sequence $(\mathsf{E}_n \mid n < \omega)$ of quasi-identities over $\mathbf{v}$, not reducible to any finite subset.

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- Nonetheless, $\mathcal{C} = \{\boldsymbol{M} \mid (\exists \text{ group structure } \boldsymbol{G} \text{ on } M)(\exists f \colon \boldsymbol{M} \hookrightarrow \boldsymbol{G})\}$ is $\mathrm{PC}(\mathscr{L}_{\omega\omega})$.

Other examples

- For a unital ring R, $\mathrm{Id}_{\mathrm{c}}\, R \stackrel{\mathrm{def}}{=} (\vee, 0)$-semilattice of all finitely generated two-sided ideals of R. Let $\mathcal{C} \stackrel{\mathrm{def}}{=} \{\mathrm{Id}_{\mathrm{c}}\, R \mid R \text{ unital ring}\}$.

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- For a commutative unital ring A, $\Phi(A) \stackrel{\text{def}}{=}$ Stone dual of the real spectrum of A (it is a bounded distributive lattice). Let $\mathcal{C} \stackrel{\text{def}}{=} \{\Phi(A) \mid A \text{ commutative unital ring}\}$.

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- All those classes are $\mathrm{PC}(\mathscr{L}_{\omega_1\omega})$.
- Observe that they are all defined as images of functors.
- We will see that none of those classes is $\text{co-}\mathrm{PC}(\mathscr{L}_{\infty\infty})$ (i.e., complement of a $\mathrm{PC}(\mathscr{L}_{\infty\infty})$).

Accessible categories and functors

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- There are many examples: $\mathbf{Str}(\mathbf{v})$, quasivarieties. . .

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PC versus accessible

Theorem (W 2021)

Let λ be a regular cardinal, let $\mathbf{v}$ be a vocabulary such that $\mathbf{v}_{\mathrm{ope}}$ is λ-ary, and let $\mathcal{C}$ be an $\mathrm{RPC}(\mathscr{L}_{\infty\lambda})$ class of $\mathbf{v}$-structures. Then there are a λ-accessible category $\mathcal{S}$ and a λ-continuous functor $\Phi\colon \mathcal{S} \to \mathbf{Str}(\mathbf{v})$, that can be taken faithful, with $\operatorname{im}\Phi \overset{\mathrm{def}}{=} \{\boldsymbol{M} \mid (\exists S \in \operatorname{Ob}\mathcal{S})(\boldsymbol{M} \cong \Phi(S))\} = \mathcal{C}$.

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The assumptions that $\mathbf{v}_{\mathrm{ope}}$, or $\mathbf{v}$, be λ-ary, cannot be dispensed with (counterexamples with idempotence, emptiness).

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Infinitely deep languages

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- The "infinitely deep language" $\mathscr{M}_{\kappa\lambda}(\mathbf{v})$ contains more general formulas than the $\partial\vec{x}\,\mathrm{E}(\vec{x})$ above, now clocked by posets which are simultaneously trees and meet-semilattices, in which every node has $<\kappa$ upper covers and every branch has length a successor $<\lambda$.

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- Satisfaction of an $\mathscr{M}_{\kappa\lambda}(\mathbf{v})$-statement is expressed *via* the existence of a winning strategy in the associated game.

Tuuri's Interpolation Theorem

Theorem (Tuuri 1992)

Let κ be a regular cardinal, let $\mathbf{v}$ be a κ-ary vocabulary, set $\lambda \stackrel{\text{def}}{=} \sup\{\kappa^\alpha \mid \alpha < \kappa\}$, and let E and F be $\mathscr{L}_{\kappa^+\kappa}(\mathbf{v})$-sentences such that the conjunction $\mathsf{E} \wedge \mathsf{F}$ has no $\mathbf{v}$-model. Then there exists an $\mathscr{M}_{\lambda^+\lambda}(\mathbf{v})$-sentence G, with vocabulary the intersection of the vocabularies of E and F, such that $\models (\mathsf{E} \Rightarrow \mathsf{G})$ and $\models (\mathsf{F} \Rightarrow \sim\mathsf{G})$.

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- Here, ${\sim}\mathsf{G}$ denotes the sentence obtained by interchanging $\bigvee\!\!\!\bigvee$ and $\bigwedge\!\!\!\bigwedge$, $\exists$ and $\forall$, A and $\neg$A in the expression of G by a tree-clocked game; it implies the usual negation $\neg\mathsf{G}$ (which, however, is no longer an $\mathscr{M}_{\lambda^+\lambda}$-sentence).

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- By a 1971 counterexample due to Malitz, $\mathscr{M}_{\lambda^+\lambda}$ cannot be replaced by $\mathscr{L}_{\infty\infty}$ in the statement of Tuuri's Theorem.

Projective and co-projective

Projective classes as images of accessible functors

Motivation

Elementary, projective

Tuuri's Interpolation Theorem

Karttunen's back-and-forth systems

Corollary

Let **v** be a vocabulary. Then for all classes $\mathcal{A}$ and $\mathcal{B}$ of **v**-structures, if $\mathcal{A}$ is $\mathrm{PC}(\mathscr{L}_{\infty\infty})$, $\mathcal{B}$ is $\text{co-PC}(\mathscr{L}_{\infty\infty})$, and $\mathcal{A} \subseteq \mathcal{B}$, then there exists an $\mathscr{M}_{\infty\infty}(\mathbf{v})$-sentence G such that $\mathcal{A} \subseteq \mathbf{Mod}_{\mathbf{v}}(\mathrm{G}) \subseteq \mathcal{B}$.

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Corollary

In order to prove that a $\mathrm{PC}(\mathscr{L}_{\infty\infty})$ class $\mathcal{C}$ of **v**-structures is not $\mathrm{co\text{-}PC}(\mathscr{L}_{\infty\infty})$, it suffices to prove that $\mathcal{C}$ is not $\mathscr{M}_{\infty\infty}(\mathbf{v})$-definable.

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But then, what is the advantage of $\mathscr{M}_{\infty\infty}$-definable over $\mathrm{PC}(\mathscr{L}_{\infty\infty})$-definable or $\text{co-}\mathrm{PC}(\mathscr{L}_{\infty\infty})$-definable?

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That's back-and-forth!

- There are several non-equivalent definitions of back-and-forth between models (extended to categorical model theory by Beke and Rosický in 2018).

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Definition (Karttunen 1979)

For a regular cardinal λ, a λ-back-and-forth system between models $\boldsymbol{M}$ and $\boldsymbol{N}$ over a vocabulary $\mathbf{v}$ consists of a poset $(\mathcal{F}, \trianglelefteq)$, together with a function $f \mapsto \overline{f}$ with domain $\mathcal{F}$, such that each $\overline{f} \colon \mathbf{d}(f) \overset{\cong}{\rightarrowtail} \mathbf{r}(f)$ with $\mathbf{d}(f) \leqslant \boldsymbol{M}$ and $\mathbf{r}(f) \leqslant \boldsymbol{N}$, and the following conditions hold:

1. $f \trianglelefteq g$ implies $\overline{f} \subseteq \overline{g}$;
2. $(\mathcal{F}, \trianglelefteq)$ is λ-inductive;
3. whenever $f \in \mathcal{F}$ and $x \in M$ (resp., $y \in N$), there is $g \in \mathcal{F}$ such that $f \subseteq g$ and $x \in \mathbf{d}(g)$ (resp., $y \in \mathbf{r}(g)$).

We then write $\boldsymbol{M} \leftrightarrows_{\lambda} \boldsymbol{N}$.

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$\mathscr{M}_{\infty\lambda}$ versus back-and-forth

Theorem (Karttunen 1979)

Let λ be a regular cardinal and let $\boldsymbol{M}$ and $\boldsymbol{N}$ be structures over a vocabulary $\mathbf{v}$. If $\boldsymbol{M} \leftrightarrows_\lambda \boldsymbol{N}$, then $\boldsymbol{M}$ and $\boldsymbol{N}$ satisfy the same $\mathscr{M}_{\infty\lambda}(\mathbf{v})$-sentences.

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- Extended by Karttunen to the even more general languages $\mathscr{N}_{\infty\lambda}$.
- The syntax for $\mathscr{N}_{\infty\lambda}$ is far more complex than for $\mathscr{M}_{\infty\lambda}$, the semantics are even trickier (not unique!).

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Establishing intractability

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In order to prove that a $\mathrm{PC}(\mathscr{L}_{\infty\infty})$ class $\mathcal{C}$ of **v**-structures is not $\text{co-PC}(\mathscr{L}_{\infty\infty})$, it suffices to prove that it is not closed under $\leftrightarrows_{\lambda}$ for a suitable regular cardinal λ.

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- Applies to earlier introduced examples $\mathrm{Id_c}$(unital rings), $\mathrm{Id_c}$(Abelian ℓ-groups), duals of real spectra of commutative unital rings, and many others: each of those classes fails to be closed under a suitable $\leftrightarrows_\lambda$.

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- The real trouble is: find a back-and-forth system $\mathcal{F}\colon \boldsymbol{M} \leftrightarrows_\lambda \boldsymbol{N}$ with $\boldsymbol{M} \in \mathcal{C}$ and $\boldsymbol{N} \notin \mathcal{C}$ (where $\mathcal{C}$ is the given class).

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- In many examples, such as Φ(unital rings) and Φ(Abelian ℓ-groups) (where $\Phi = \mathsf{Id}_{\mathsf{c}}$), $\leftrightarrows_\lambda$ arises from some λ-continuous functor $\Gamma\colon [\kappa]^{\mathrm{inj}} \to \mathcal{C}$ with $\kappa \geq \lambda$.

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- It is often the case that for $X \subseteq \kappa$ with $\operatorname{card} X < \lambda$, $\Gamma(X) = \Phi\left(\prod(S_{|u|} \mid u \in X^{\subseteq P})\right)$ (a "condensate"), where:
  1. P is a suitable finite lattice (in both examples above, $P = \{0,1\}^3$; also, this method provably fails for arbitrary finite bounded posets!);
  2. $X^{\subseteq P} \stackrel{\mathrm{def}}{=} \bigcup\{X^D \mid D \subseteq P\}$;
  3. $|u| \stackrel{\mathrm{def}}{=} \bigvee \operatorname{dom} u$ whenever $u \in X^{\subseteq P}$;
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Back-and-forth systems from continuous functors

- In many examples, such as $\Phi(\text{unital rings})$ and $\Phi(\text{Abelian } \ell\text{-groups})$ (where $\Phi = \mathsf{Id}_{\mathsf{c}}$), $\leftrightarrows_\lambda$ arises from some λ-continuous functor $\Gamma\colon [\kappa]^{\mathrm{inj}} \to \mathcal{C}$ with $\kappa \geq \lambda$. Here, $[\kappa]^{\mathrm{inj}}$ denotes the category of all subsets of κ with one-to-one functions. In both examples above, $\kappa = \lambda^{++}$.
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- Finding P and $\vec{S}$ is usually hard, very much connected to the algebraic and combinatorial data of the given problem.

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The diagram $\vec{S}$ for $\mathrm{Id_c}$(Abelian ℓ-groups)

$$\begin{tikzcd}
 & A_{123}(a, a', b, c) & \\
A_{12}(a, b) \arrow[ur] & A_{13}(a', c) \arrow[u] & A_{23}(b, c) \arrow[ul] \\
A_1(a) \arrow[u] \arrow[ur] & A_2(b) \arrow[ul] \arrow[ur] & A_3(c) \arrow[u] \arrow[ul] \\
 & A_\varnothing = \{0\} \arrow[ul] \arrow[u] \arrow[ur] &
\end{tikzcd}$$

$0 \leq a \leq a' \leq 2a;\ b \geq 0;\ c \geq 0.$
$A_1(a) \to A_{13}(a', c)$ *via* $a \mapsto a'$.

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- Denote by $\mathcal{A}$ the class of all Abelian ℓ-groups, and by $\mathsf{Id_c}\,\mathcal{A}$ the class of all isomorphic copies of $\mathsf{Id_c}\,G$ where $G \in \mathcal{A}$. It is $\mathrm{PC}(\mathscr{L}_{\omega_1\omega})$, but, by the above, not $\text{co-PC}(\mathscr{L}_{\infty\infty})$.

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A further example with Abelian ℓ-groups

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- A bounded distributive lattice D satisfies Ploščica's Condition if for every $a \in D$ and every collection $(\mathfrak{m}_i \mid i \in I)$ of maximal ideals of $\downarrow a$, $\downarrow a / \bigcap_i \mathfrak{m}_i$ has cardinality $\leq 2^{\mathrm{card}\, I}$ (careful with definition of $\downarrow a/J$).

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Theorem (Ploščica 2021)

Every member of $\mathrm{Id}_{\mathrm{c}}\,\mathcal{A}$ satisfies Ploščica's Condition.

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Theorem (W 2022, under a fragment of GCH)

There exists a bounded distributive lattice, of cardinality $\aleph_4$, satisfying all known $\mathscr{L}_{\omega_1\omega_1}$ properties of all members of $\mathrm{Id_c}\,\mathcal{A}$ together with Ploščica's Condition, but not in $\mathrm{Id_c}\,\mathcal{A}$.

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Thanks for your attention!

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