Keisler's theorem and cardinal invariants at uncoutable cardinals

Tatsuya Goto

Kobe University

February 1, 2024

Keisler–Shelah theorem

For every (first-order) language $\mathcal{L}$ and two $\mathcal{L}$-structures $\mathcal{A}, \mathcal{B}$, the following are equivalent:

1. $\mathcal{A} \equiv \mathcal{B}$ (that is, $\mathcal{A}$ and $\mathcal{B}$ are elementarily equivalent).
2. There is a nonprincipal ultrafilter $\mathcal{U}$ over an infinite set such that the ultrapowers $\mathcal{A}^{\mathcal{U}}$ and $\mathcal{B}^{\mathcal{U}}$ are isomorphic.

(2) $\Rightarrow$ (1) is obvious. Keisler proved (1) $\Rightarrow$ (2) under GCH. Shelah eliminated GCH assumption.

How about versions with restrictions on the cardinalities of languages, structures and the underlying sets of ultrafilters?

Keisler–Golshani–Shelah theorem

Keisler–Golshani–Shelah theorem (Keisler, Golshani and Shelah)

The following are equivalent:

1. The continuum hypothesis.
2. For every countable language $\mathcal{L}$ and two $\mathcal{L}$-structures $\mathcal{A}, \mathcal{B}$ of size $\leqslant \mathfrak{c}$, if $\mathcal{A} \equiv \mathcal{B}$ then there is a nonprincipal ultrafilter $\mathcal{U}$ over ω such that the ultrapowers $\mathcal{A}^{\mathcal{U}}$ and $\mathcal{B}^{\mathcal{U}}$ are isomorphic.

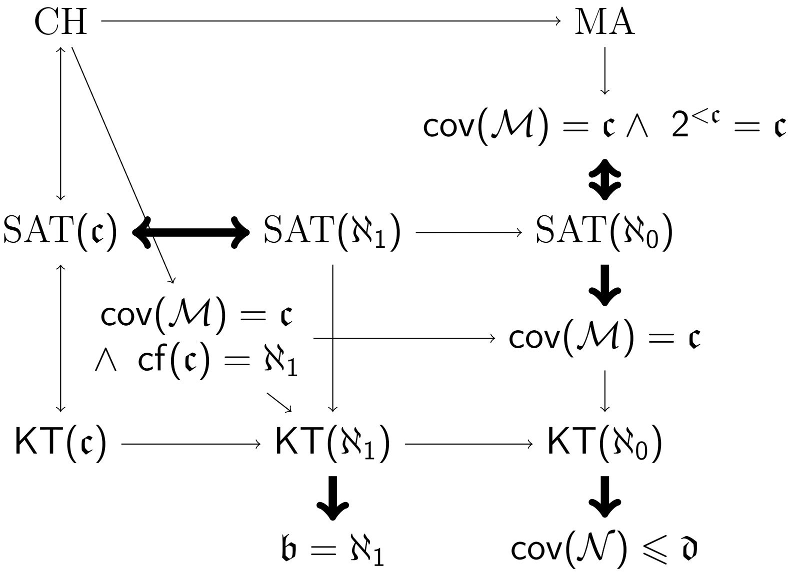
(1) $\Rightarrow$ (2) was proved by Keisler (1961) and (2) $\Rightarrow$ (1) is due to Golshani and Shelah (2022).

The principles

Let λ be a cardinal.

1. We say $\mathrm{KT}(\lambda)$ holds if for every countable language $\mathcal{L}$ and $\mathcal{L}$-structures $\mathcal{A}, \mathcal{B}$ of size $\leqslant \lambda$ which are elementarily equivalent, there exists an ultrafilter $\mathcal{U}$ over ω such that $\mathcal{A}^\omega/\mathcal{U} \simeq \mathcal{B}^\omega/\mathcal{U}$.
2. We say $\mathrm{SAT}(\lambda)$ holds if there exists an ultrafilter $\mathcal{U}$ over ω such that for every countable language $\mathcal{L}$ and every sequence of $\mathcal{L}$-structures $(\mathcal{A}_i)_{i\in\omega}$ with each $\mathcal{A}_i$ of size $\leqslant \lambda$, $\prod_{i\in\omega} \mathcal{A}_i/\mathcal{U}$ is saturated.

The implications (thick lines are due to the speaker)



Let's generalize these principles much more!

The generalized principles

Let κ, μ and λ be infinite cardinals.

$\mathsf{KT}^{\mu}_{\kappa}(\lambda) \iff$ for every language $\mathcal{L}$ of size $\leqslant \mu$ and
every elementarily equivalent $\mathcal{L}$-structures $\mathcal{A}, \mathcal{B}$ of size $\leqslant \lambda$,
there is a uniform ultrafilter $\mathcal{U}$ on κ such that $\mathcal{A}^{\mathcal{U}} \simeq \mathcal{B}^{\mathcal{U}}$.

$\mathrm{SAT}^{\mu}_{\kappa}(\lambda) \iff$ there is a uniform ultrafilter $\mathcal{U}$ on κ such that
for every language $\mathcal{L}$ of size $\leqslant \mu$ and
every sequence $\langle \mathcal{A}_i : i < \kappa \rangle$ of infinite $\mathcal{L}$-str. of size $\leqslant \lambda$,
the ultraproduct $\left(\prod_{i \in \kappa} \mathcal{A}_i \right) / \mathcal{U}$ is saturated.

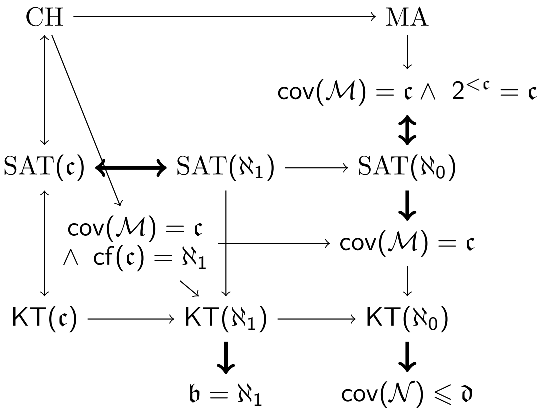
Keisler-Shelah theorem in this context

The statement of Keisler-Shelah theorem can be said as $\mathsf{KT}^{2^\kappa}_{2^\kappa}(\kappa)$.

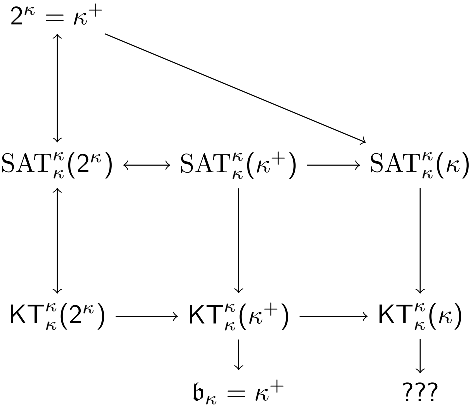
$\mathsf{KT}^{\text{size of language}}_{\text{length of ultrapower}}(\text{size of structures})$

The implications

The countable case



The general case



Results

$\mathrm{KT}^{\text{size of language}}_{\text{length of ultrapower}}(\text{size of structures})$

1. $\mathrm{SAT}^{\mu}_{\kappa}(\lambda)$ implies $\mathrm{KT}^{\mu}_{\kappa}(\lambda)$.
2. $\neg\mathrm{SAT}^{\aleph_0}_{\kappa}(\kappa^{++})$.
3. $\neg\,\mathrm{KT}^{\aleph_0}_{\kappa}(\kappa^{++})$.
4. $\mathrm{SAT}^{\aleph_0}_{\kappa}(\kappa^{+})$ implies $2^{\kappa} = \kappa^{+}$.
5. The following are equivalent.

   a. $2^{\kappa} = \kappa^{+}$. b. $\mathrm{SAT}^{\mu}_{\kappa}(2^{\kappa})$. c. $\mathrm{SAT}^{\mu}_{\kappa}(\kappa^{+})$. d. $\mathrm{KT}^{\mu}_{\kappa}(2^{\kappa})$.
6. $\mathrm{SAT}^{\aleph_0}_{\kappa}(\kappa)$ implies $2^{<2^{\kappa}} = 2^{\kappa}$.
7. When κ is regular, $\mathrm{KT}^{\aleph_0}_{\kappa}(\kappa^{+})$ implies $\mathfrak{b}_{\kappa} = \kappa^{+}$.

The meager ideal on κ

Let κ be a regular cardinal. Topologize $2^\kappa = \{0, 1\}^\kappa$ by $<\kappa$-box topology, where $\{0, 1\}$ is the discrete space. Then the meager ideal on 2^κ is κ-additive ideal generated by nowhere dense sets of 2^κ.

Let $\mathrm{cov}(\mathcal{M}_\kappa)$ be the covering number of the meager ideal of 2^κ.

Results related to $\mathrm{cov}(\mathcal{M}_\kappa)$

1. When κ is a regular cardinal, $\mathrm{cov}(\mathcal{M}_\kappa) = 2^\kappa$ implies $\mathrm{KT}_\kappa^\mu(\kappa)$ for $\mu < 2^\kappa$.
2. When κ is an **inaccessible** cardinal, $\mathrm{SAT}_\kappa^{\aleph_0}(\kappa)$ implies $\mathrm{cov}(\mathcal{M}_\kappa) = 2^\kappa$.
   - We showed this result by using van der Vlugt's theorem extending Bartoszynski's characterization of $\mathrm{cov}(\mathcal{M})$ in terms of slaloms.
3. When κ is a regular cardinal, $\mathrm{cov}(\mathcal{M}_\kappa) = 2^{<2^\kappa} = 2^\kappa$ implies $\mathrm{SAT}_\kappa^\kappa(\kappa)$.

Results related to $\text{cov}(\mathcal{M}_\kappa)$

van der Vlugt's theorem Let κ be an inaccessible cardinal. Then $\text{cov}(\mathcal{M}_\kappa) \geqslant \lambda$ holds iff for every $X \subseteq \kappa^\kappa$ of size $<\lambda$ there is $S \in \prod_{i<\kappa}[\kappa]^{[\leqslant|i|+1}$ for all $x \in X$ we have $\{i < \kappa : x(i) \in S(i)\}$ is cofinal in κ.

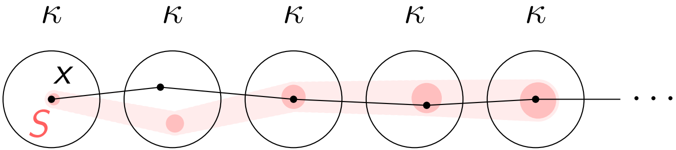


Figure: photo © Ola Matsson — Trysil, Hedmark Fylke, NO

Results related to $\mathrm{cov}(\mathcal{M}_\kappa)$

Theomem (G.) Let κ be inaccessible. Then $\mathrm{SAT}^{\aleph_0}_\kappa(\kappa)$ implies $\mathrm{cov}(\mathcal{M}_\kappa) = 2^\kappa$.

Let $\mathcal{U}$ be a regular ultrafilter on κ witnessing $\mathrm{SAT}^{\aleph_0}_\kappa(\kappa)$. Let $X \subseteq \kappa^\kappa$ of size $<2^\kappa$. Let $\mathcal{L} = \{\subseteq\}$. For $i < \kappa$, define a $\mathcal{L}$-structure $\mathcal{A}_i$ by $\mathcal{A}_i = ([\kappa]^{<|i|}, \subseteq)$. For $x \in \kappa^\kappa$, we define $S_x = \langle \{x(i)\} : i < \kappa \rangle$. Put $\mathcal{A}_* = \prod_{i<\kappa} \mathcal{A}_i / \mathcal{U}$. Consider a set of formulas $p(S)$ defined by

$$p(S) = \{\ulcorner [S_x] \subseteq S \urcorner : x \in X\}.$$

Then $p(S)$ is finitely satisfiable and number of parameters occurring in $p(S)$ is $<2^\kappa$. Thus, by $\mathrm{SAT}^{\aleph_0}_\kappa(\kappa)$, we can take $[S] \in \mathcal{A}_*$ realizing $p(S)$.

Then we have

$$(\forall x \in X)(\{i < \kappa : x(i) \in S(i)\} \in \mathcal{U}).$$

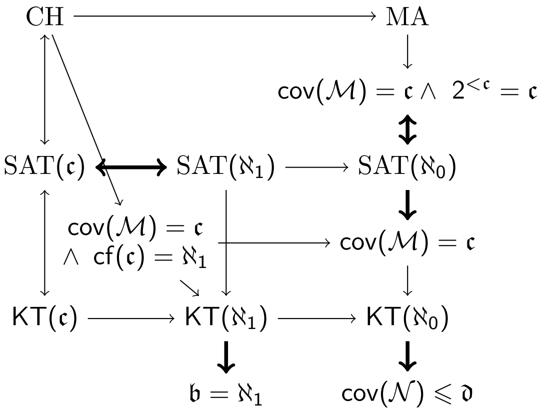
But since our ultrafilter $\mathcal{U}$ is uniform, we have

$$(\forall x \in X)(\{i < \kappa : x(i) \in S(i)\} \text{ is cofinal}).$$

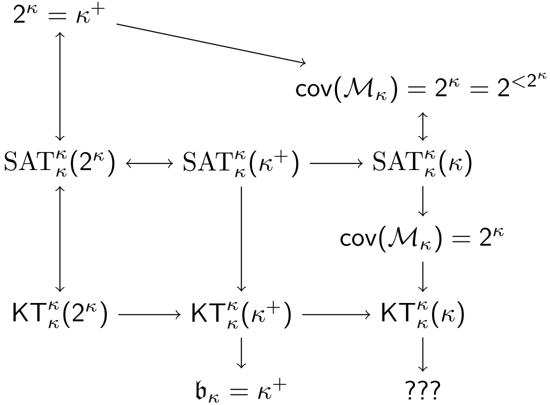
So by van der Vlught's theorem, we showed $\mathrm{cov}(\mathcal{M}_\kappa) = 2^\kappa$.

The implications

The countable case

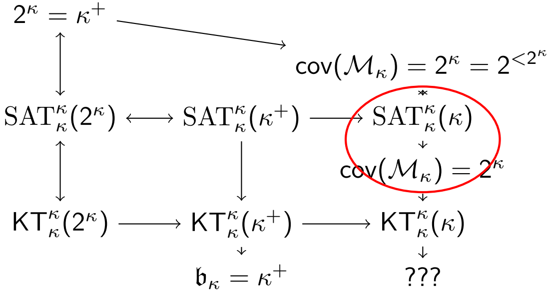


The **inaccessible** case



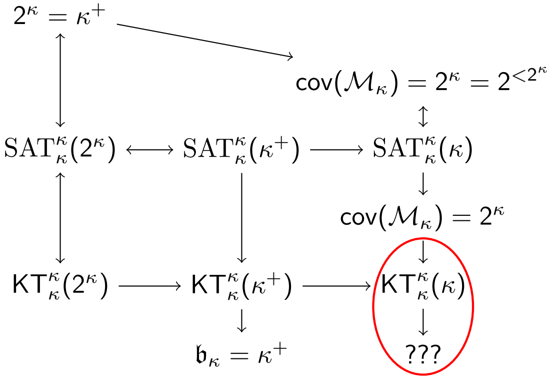
Questions

1. Can we eliminate the inaccessibility assumption from the result which states $\mathrm{SAT}_\kappa^{\aleph_0}(\kappa)$ implies $\mathrm{cov}(\mathcal{M}_\kappa) = 2^\kappa$.
   - Note that when κ is a successor and $2^{\kappa^-} > \kappa$, we have $\mathrm{cov}(\mathcal{M}_\kappa) = \kappa^+$.
   - Note also that when κ is a successor, "The minimum cardinality of $X \subseteq \kappa^\kappa$ such that there is no $S \in \prod_{i<\kappa}[\kappa]^{\leqslant|i|+1}$ such that for all $x \in X$, $\{i < \kappa : x(i) \in S(i)\}$ is cofinal in κ" is equal to $\mathfrak{d}_\kappa$.



Questions

2. Can we prove the consistency of $\neg\,\mathsf{KT}^{\kappa}_{\kappa}(\kappa)$?
   - Recall that $\mathsf{KT}^{\aleph_0}_{\aleph_0}(\aleph_0)$ implies $\mathrm{cov}(\mathcal{N}) \leqslant \mathfrak{d}$.



References

[Kei64] H Jerome Keisler. "Ultraproducts and saturated models". In: *Indag. Math* 26 (1964), pp. 178–186.

[She71] Saharon Shelah. "Every two elementarily equivalent models have isomorphic ultrapowers". In: *Israel Journal of Mathematics* 10.2 (1971), pp. 224–233.

[Got22] Tatsuya Goto. "Keisler's theorem and cardinal invariants". In: *The Journal of Symbolic Logic* (2022), pp. 1–13.

[GS23] Mohammad Golshani and Saharon Shelah. "The Keisler-Shelah isomorphism theorem and the continuum hypothesis". In: *Fund. Math.* 260.1 (2023). arXiv: 2108.03977, pp. 59–66.

[Vlu23] Tristan van der Vlugt. *Cardinal Characteristics on Bounded Generalised Baire Spaces*. 2023. arXiv: 2307.14118 [math.LO].

[Tsu22] Akito Tsuboi. "Some results related to Keisler-Shelah isomorphism theorem (Model theoretic aspects of the notion of independence and dimension)". In: *RIMS Kôkyûroku* 2218 (May 2022).