

KLEINBERG SEQUENCES AND PARTITION CARDINALS BELOW δ_5^1

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ABSTRACT. The author computes the Kleinberg sequences derived from the three different normal ultrafilters on δ_3^1 .

1. INTRODUCTION

Eugene Kleinberg linked the theory of partition cardinals with the Axiom of Determinacy AD by showing that the first $\omega + 1$ infinite cardinals satisfy certain large cardinal properties defined via partition relations. Indeed, his proof didn't actually use the Axiom of Determinacy but some of its consequences.

More generally, Kleinberg showed (for a proof, *cf.* [K177] or (for a more thorough presentation) [Sch99]):

Theorem 1.1. Let κ be a cardinal with the strong partition property and μ be a normal ultrafilter on κ . Let $\kappa_1 := \kappa$ and $\kappa_{n+1} := \kappa_n^\kappa / \mu$. Then

- (i) κ_1 and κ_2 are measurable,
- (ii) for all $n \geq 2$, $\text{cf}(\kappa_n) = \kappa_2$,
- (iii) κ_n is a Jónsson cardinal, and
- (iv) $\sup\{\kappa_n; n \in \omega\}$ is a Rowbottom cardinal.

Moreover, if $\kappa^\kappa / \mu = \kappa^+$, then $\kappa_{n+1} = (\kappa_n)^+$ for all $n \in \omega$.

Corollary 1.2. Assume AD. Then for all positive natural numbers n , $\aleph_n$ is a Jónsson cardinal and $\aleph_\omega$ is a Rowbottom cardinal.

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Proof : After a brief look at Theorem 1.1 we realize that nothing is to show if $\aleph_1$ has the strong partition property and $\aleph_1^{\aleph_1}/\mu = \aleph_2$ for some (the only) normal ultrafilter μ on $\aleph_1$. But the first assertion is a theorem of Martin (*cf.* [Ka94, Theorem 28.12]), the second is a theorem of Solovay (*cf.* [Kl77, Theorem 2.9]). q.e.d.

At that time, it was unknown whether there are any natural assumptions (e.g., the Axiom of Determinacy) under which the conditions of Kleinberg's Theorem 1.1 are met except for the case mentioned in the proof of Corollary 1.2.

The deep structural results of Jackson's computation of δ_5^1 immediately provided additional examples for Kleinberg's theorem under AD: All odd projective ordinals δ_{2n+1}^1 are starting points for sequences of successive Jónsson cardinals derived from the ω -cofinal normal ultrafilter (*cf.* Theorem 2.5 and Fact 2.4 (vii)).

But Kleinberg's Theorem 1.1 provides us with even more sequences of Jónsson cardinals starting from δ_{2n+1}^1 since we have as many normal measures on δ_{2n+1}^1 as we have regular cardinals below it. Where exactly are these Jónsson and Rowbottom cardinals? Can we compute the cardinality of the members of these additional Kleinberg sequences?

In this note we shall answer these questions and compute the Kleinberg sequences derived from the ω_1 -cofinal and the ω_2 -cofinal measures on δ_3^1 . An important ingredient here is the exact knowledge of cofinalities of successor cardinals between δ_3^1 and δ_5^1 provided by [JaKh ∞].

2. PREREQUISITES AND THE SHIFTING LEMMA

To compute the Kleinberg sequences, we will use a substantial amount of knowledge about the behaviour of the projective ordinals and of the combinatorial theory below δ_5^1 under AD. Nevertheless we try to keep the paper understandable for readers with a basic understanding of Determinacy and Large Cardinals by listing all theorems that we shall use later on in this section.

Any readers interested in the basic theory (and definitions) of Jónsson and Rowbottom cardinals are referred to [Ka94, §7 & §8].

Definition 2.1. Let κ be a cardinal. We shall say that κ has the **strong partition property** if $\kappa \rightarrow (\kappa)^\kappa$ holds, i.e. if for every partition of $[\kappa]^\kappa$ into two blocks there is a homogeneous set of order type κ .

Note that the strong partition property cannot hold for any cardinal if we assume the Axiom of Choice AC: by a result of Erdős and Rado

(cf. [Ka94, Proposition 7.1]) no partition relation can have infinite exponents if the Axiom of Choice holds.

That the strong partition property of κ really is a property with astonishing consequences for the combinatorial theory of κ (or, to put it in Jim Henle's words, that it is "one of the most powerful partition properties known to man [He79, p. 151]"), can be seen in the next result of Kleinberg, a proof of which can be found in [Ka94, Theorem 28.10 & Exercise 28.11]:

Theorem 2.2. Let κ be a cardinal with the strong partition property and $\lambda < \kappa$ a regular cardinal. Then $\mathcal{C}_\kappa^\lambda$, the filter generated by the λ -closed unbounded sets in κ , is a normal ultrafilter on κ . We call $\mathcal{C}_\kappa^\lambda$ the λ -**cofinal filter** or **measure**.

In addition, if κ is not weakly Mahlo, then these are the only normal ultrafilters on κ .

The reader was already informally introduced to Kleinberg sequences in Theorem 1.1. Now we fix our notation:

Definition 2.3. Let κ be a cardinal with the strong partition property and μ a normal measure on κ . We then define a sequence of well-ordered structures $\langle \kappa_n^\mu; n \leq \omega \rangle$ as follows:

- $\kappa_1^\mu := \kappa$,
- $\kappa_{n+1}^\mu := (\kappa_n^\mu)^\kappa / \mu$, and
- $\kappa_\omega^\mu := \sup\{\kappa_n^\mu; n \in \omega\}$.

This sequence is called the **Kleinberg sequence derived from μ** .

As we already mentioned in Theorem 1.1, all elements of a Kleinberg sequence are Jónsson cardinals, and κ_ω is a Rowbottom cardinal.

We define the projective ordinals by

$$\delta_n^1 := \sup\{\xi; \xi \text{ is the length of a prewellordering of } \omega^\omega \text{ in } \Delta_n^1\}.$$

Even before Jackson's results, a couple of things were known about the projective ordinals under AD:

Fact 2.4. Let n be a natural number. Assume AD. Then:

- (i) (Kunen, Martin 1971) $\delta_{2n+2}^1 = (\delta_{2n+1}^1)^+$,
- (ii) (Kechris 1974) δ_{2n+1}^1 is the cardinal successor of a cardinal of cofinality ω ,
- (iii) (Martin, Kunen 1971) all δ_n^1 are measurable,
- (iv) (Martin, Kunen 1971) $\delta_2^1 = \aleph_2$, $\delta_3^1 = \aleph_{\omega+1}$, and $\delta_4^1 = \aleph_{\omega+2}$,
- (v) (Martin, Paris 1971) $\delta_1^1 \rightarrow (\delta_1^1)^{\delta_1^1}$, and for all $\alpha < \delta_2^1$, the relation $\delta_2^1 \rightarrow (\delta_2^1)^\alpha$ holds,

- (vi) (Martin 1971) for all $\alpha < \omega_1$ the partition relation $\delta_{2n+1}^1 \rightarrow (\delta_{2n+1}^1)^\alpha$ holds,
- (vii) (Kunen 1971) the ω -cofinal measure $\mathcal{C}_{\delta_{2n+1}^1}^\omega$ is a normal measure on δ_{2n+1}^1 with $\delta_{2n+1}^1 / \mathcal{C}_{\delta_{2n+1}^1}^\omega = \delta_{2n+2}^1$, and
- (viii) (Martin 1980) $\delta_3^1 / \mathcal{C}_{\delta_3^1}^{\omega_1} = \aleph_{\omega \cdot 2 + 1}$ and $\delta_3^1 / \mathcal{C}_{\delta_3^1}^{\omega_2} = \aleph_{\omega^\omega + 1}$, and these two cardinals are measurable.

Proof : A proof of all parts except for the last can be found in [Ke78]. Fact 2.4 comprises of Theorem 3.12, Theorem 3.10, Theorem 5.1, §6, Theorem 12.1, Corollary 13.4, Theorem 11.2, and Theorem 14.3 of [Ke78]. The last is part of [Ja ∞ , Chapter 7]. q.e.d.

Since the values of δ_1^1 , δ_2^1 , δ_3^1 , and δ_4^1 were known, the next open question was the value of δ_5^1 . This was the content of the First Victoria Delfino Problem (cf. [KeMo78]) and was solved by Steve Jackson who computed δ_5^1 to be $\aleph_{\omega^\omega + 1}$ (cf. [Ja88] and [Ja ∞]):

Theorem 2.5. Assume AD. Let E be the function recursively defined by $E(0) = 1$ and $E(n+1) = \omega^{E(n)}$. Then for every $n \in \omega$,

$$\delta_{2n+1}^1 = \aleph_{E(2n+1)+1},$$

and all odd projective ordinals have the strong partition property.

This computation gave rise to a detailed analysis of the cardinals between δ_3^1 and δ_5^1 that will be used in this note.

The main tool of our computation will be the following theorem which is an elaboration of the proof of the “moreover” part in Theorem 1.1:

Ultrapower Shifting Lemma 2.6. Let $\kappa = \aleph_\alpha < \lambda = \aleph_{\alpha+\beta}$, and let μ be a κ -complete ultrafilter on κ . Let γ be such that $\kappa^\kappa / \mu = \aleph_\gamma$.

Suppose that for all cardinals ν such that $\kappa < \nu \leq \lambda$ the following holds:

- (i) Either ν is a successor and $\text{cf}(\nu) > \kappa$,
- (ii) or ν is a limit and $\text{cf}(\nu) < \kappa$.

Then $\lambda^\kappa / \mu \leq \aleph_{\gamma+\beta}$.

Proof : The proof proceeds by induction on β . The case $\beta = 0$ is just the definition of γ .

For the successor step suppose that $\lambda = \aleph_{\alpha+\beta+1}$ and that $\aleph_{\alpha+\beta}^\kappa / \mu \leq \aleph_{\gamma+\beta}$.

Pick any $\eta \in \lambda^\kappa/\mu$. Let $f : \kappa \rightarrow \lambda$ be a function representing η , so $\eta = [f]_\mu$. Since $\text{cf}(\lambda) > \kappa$, we know that $\text{ran}(f)$ is bounded in λ , say by $\eta^* < \lambda$. Hence $\eta = \{\nu; \nu < \eta^*\} \subseteq (\eta^*)^\kappa/\mu$.

But $\text{Card}((\eta^*)^\kappa/\mu) = \text{Card}((\text{Card}(\eta^*)^\kappa/\mu) \leq \aleph_{\gamma+\beta}$ by the induction hypothesis. Thus every ordinal in λ^κ/μ has cardinality $\leq \aleph_{\gamma+\beta}$, consequently $\lambda^\kappa/\mu \leq \aleph_{\gamma+\beta+1}$.

Now we look at the limit step, where χ is a limit ordinal and for all $\beta < \chi$ we have $\aleph_{\alpha+\beta}^\kappa/\mu \leq \aleph_{\gamma+\beta}$.

We show that $\aleph_{\alpha+\chi}^\kappa/\mu = \bigcup_{\beta < \chi} \aleph_{\alpha+\beta}^\kappa/\mu$. This shows the claim, since

$$\begin{aligned} \text{Card}\left(\bigcup_{\beta < \chi} \aleph_{\alpha+\beta}^\kappa/\mu\right) &\leq \sup\{\text{Card}(\aleph_{\alpha+\beta}^\kappa/\mu); \beta < \chi\} \\ &\leq \sup\{\aleph_{\gamma+\beta}; \beta < \chi\} = \aleph_{\gamma+\chi}. \end{aligned}$$

As the backwards inclusion is clear, we proceed to the other direction. Take $\eta \in \aleph_{\alpha+\chi}^\kappa/\mu$ and a function $f : \kappa \rightarrow \aleph_{\alpha+\chi}$ with $[f]_\mu = \eta$. Let $\langle B_\delta; \delta < \text{cf}(\chi) \rangle$ be a disjoint family of sets of cardinality $\text{Card}(B_\delta) < \aleph_{\alpha+\chi}$ none of which is cofinal in $\aleph_{\alpha+\chi}$ (e.g., the intervals determined by a cofinal sequence of length $\text{cf}(\chi)$).

Now define $F_\delta := (f^{-1})'' B_\delta$. Then $\langle F_\delta; \delta < \text{cf}(\chi) \rangle$ is a disjoint partition of κ into less than κ sets (by assumption on $\text{cf}(\chi)$), hence by κ -completeness there is a δ_0 such that $F_{\delta_0} \in \mu$.

But B_{δ_0} was not cofinal in $\aleph_{\alpha+\chi}$, so we can set $\beta_0 := \sup(B_{\delta_0}) + 1 < \aleph_{\alpha+\chi}$, and define $f_0(\xi) := \min(f(\xi), \beta_0)$. Let $\beta_1 < \chi$ be the unique ordinal such that $\text{Card}(\beta_0) = \aleph_{\alpha+\beta_1}$.

Then $f_0 : \kappa \rightarrow \aleph_{\alpha+\beta_1+1}$ and $[f_0]_\mu = [f]_\mu$, hence $\eta \in \aleph_{\alpha+\beta_1+1}^\kappa/\mu$. **q.e.d.**

3. COMPUTATIONS OF THE KLEINBERG SEQUENCES

By Theorem 2.2, we have exactly three normal ultrafilters $\mu_0 := \mathcal{C}_{\delta_3^1}^\omega$, $\mu_1 := \mathcal{C}_{\delta_3^1}^{\omega_1}$, and $\mu_2 := \mathcal{C}_{\delta_3^1}^{\omega_2}$ on δ_3^1 , corresponding to the three regular cardinals $\aleph_0$, $\aleph_1$, and $\aleph_2$ below δ_3^1 . Using the fact that δ_3^1 has the strong partition property by Theorem 2.5 and Kleinberg's Theorem 1.1, we receive three Kleinberg sequences $\langle \kappa_n^{\mu_0}; n \leq \omega \rangle$, $\langle \kappa_n^{\mu_1}; n \leq \omega \rangle$, and $\langle \kappa_n^{\mu_2}; n \leq \omega \rangle$.

The first of these is completely known — it is derived from the ω -cofinal filter on δ_3^1 and thus satisfies the “moreover” part of Theorem 1.1 by Fact 2.4 (vii). Therefore we have $\kappa_n^{\mu_0} = \aleph_{\omega+n}$ for all $n \leq \omega$.

By Fact 2.4 (viii), we know the values of $\kappa_2^{\mu_1} = \aleph_{\omega \cdot 2 + 1}$ and $\kappa_2^{\mu_2} = \aleph_{\omega \cdot 2 + 1}$. So we are left with computing the higher values of $\kappa_n^{\mu_1}$ and $\kappa_n^{\mu_2}$.

This is made possible by the exact computations of cofinalities below δ_5^1 by Jackson and Khafizov in [JaKh ∞]:

Theorem 3.1. Suppose $\delta_3^1 < \aleph_{\alpha+1} < \delta_5^1$. Let $\alpha = \omega^{\beta_1} + \dots + \omega^{\beta_n}$, where $\omega^\omega > \beta_1 \geq \dots \geq \beta_n$ be the normal form for α . Then:

- If $\beta_n = 0$, then $\text{cf}(\aleph_{\alpha+1}) = \delta_4^1 = \aleph_{\omega+2}$,
- if $\beta_n > 0$, and is a successor ordinal, then $\text{cf}(\aleph_{\alpha+1}) = \aleph_{\omega \cdot 2 + 1}$, and
- if $\beta_n > 0$ and is a limit ordinal, then $\text{cf}(\aleph_{\alpha+1}) = \aleph_{\omega^\omega + 1}$.

We come now to the main result of this note:

Theorem 3.2. Assume AD and the above notation. Let $n \geq 1$. Then $\kappa_n^{\mu_1} = \aleph_{\omega \cdot n + 1}$ and $\kappa_n^{\mu_2} = \aleph_{\omega + \omega^\omega \cdot (n-1) + 1}$

Proof : Both cases proceed by induction. The case $n = 1$ is Fact 2.4 (viii) as mentioned above.

We start with the ω_1 sequence. By definition $\kappa_{n+1}^{\mu_1} = (\kappa_n^{\mu_1})^{\delta_3^1} / \mathcal{C}_{\delta_3^1}^{\omega_1}$, and by induction hypothesis we know that $\kappa_n^{\mu_1} = \aleph_{\omega \cdot n + 1} = \aleph_{\omega + 1 + \omega \cdot (n-1) + 1}$.

Looking at the Ultrapower Shifting Lemma 2.6 with $\alpha = \omega + 1$, $\beta = \omega \cdot (n-1) + 1$, and $\gamma = \omega \cdot 2 + 1$, we get

$$\kappa_{n+1}^{\mu_1} = (\kappa_n^{\mu_1})^{\delta_3^1} / \mathcal{C}_{\delta_3^1}^{\omega_1} \leq \aleph_{\omega \cdot 2 + 1 + \omega \cdot (n-1) + 1} = \aleph_{\omega \cdot (n+1) + 1}.$$

By Theorem 1.1, we know that $\text{cf}(\kappa_{n+1}^{\mu_1}) = \aleph_{\omega \cdot 2 + 1}$. But between $\kappa_n^{\mu_1}$ and $\aleph_{\omega \cdot (n+1) + 1}$, there is according to Theorem 3.1 exactly one cardinal with cofinality $\aleph_{\omega \cdot 2 + 1}$, and this is $\aleph_{\omega \cdot (n+1) + 1}$ itself. So $\kappa_{n+1}^{\mu_1} = \aleph_{\omega \cdot (n+1) + 1}$.

The case ω_2 works exactly the same way: We apply the Ultrapower Shifting Lemma 2.6, this time with $\alpha = \omega + 1$, $\beta = \omega^\omega \cdot n + 1$, and $\gamma = \omega^\omega + 1$, and then check using Theorem 3.1 that there is only one possibility left. q.e.d.

Note that Theorem 3.2 together with the proof of Lemma 2.6 also gives some information about the lengths of several other ultrapowers: *E.g.*, suppose that $\aleph_{\omega \cdot 2}^{\delta_3^1} / \mathcal{C}_{\delta_3^1}^{\omega_1} < \aleph_{\omega \cdot 3}$. In this case, by the proof of Lemma 2.6, $\kappa_3^{\mu_1}$ cannot be $\aleph_{\omega \cdot 3 + 1}$, contradicting Theorem 3.2. Hence $\aleph_{\omega \cdot 2}^{\delta_3^1} / \mathcal{C}_{\delta_3^1}^{\omega_1} = \aleph_{\omega \cdot 3}$.

Now we are prepared to harvest the fruits of our work:

Corollary 3.3. Assume AD. Then the cardinals $\aleph_{\omega \cdot n + 1}$ and $\aleph_{\omega^\omega \cdot n + 1}$ are Jónsson for every $n \in \omega$. Furthermore, the cardinals $\aleph_{\omega^2}$ and $\aleph_{\omega^\omega \cdot \omega}$ are Rowbottom.

Proof : Immediate from Theorem 3.2 and Theorem 1.1. q.e.d.

4. OTHER CARDINALS BELOW AND BEYOND δ_5^1

There are much more cardinals between δ_3^1 and δ_5^1 than the ones we managed to reach with the three Kleinberg sequences. There is nothing known about large cardinal properties of these cardinals. *E.g.*, nothing is known about $\aleph_{\omega \cdot 2} + 2$ which, incidentally, is the first infinite cardinal of which we don't know that it has any large cardinal properties under AD. The results in this paper might shed some light on the limit cardinals, though: $\aleph_{\omega \cdot 3}$, the first limit cardinal without known large cardinal properties, is the ultrapower of a Rowbottom cardinal with a normal ultrafilter according to the remark after Theorem 3.2. This fact might prove to be useful for a more thorough investigation of $\aleph_{\omega \cdot 3}$ and comparable cardinals.

Even more interesting seems the glance beyond δ_5^1 . Jackson in his [Ja99] lists the seven measurable cardinals between δ_5^1 and δ_7^1 as: $\delta_7^1 = \aleph_{\omega^{\omega\omega}+2}$, $\aleph_{\omega^{\omega\omega}+\omega+1}$, $\aleph_{\omega^{\omega\omega}+\omega^{\omega+1}}$, $\aleph_{\omega^{\omega\omega} \cdot 2+1}$, $\aleph_{\omega^{\omega\omega+1}+1}$, $\aleph_{\omega^{\omega\omega \cdot 2}+1}$, and $\aleph_{\omega^{\omega\omega\omega}+1}$. These cardinals are the ultrapowers of δ_5^1 with the seven normal ultrafilters on δ_5^1 , hence they are the second cardinals in the seven Kleinberg sequences derived from these filters. To apply Lemma 2.6 to these sequences and compute the Jónsson cardinals between δ_5^1 and δ_7^1 only one piece of information is missing: the analysis of cofinalities corresponding to Theorem 3.1.

REFERENCES

- [He79] James M. **Henle**, Researches into the world of $\kappa \rightarrow (\kappa)^\kappa$, *Annals of Mathematical Logic* 17 (1979), p. 151–169
- [Ja88] Steve **Jackson**, AD and the Projective Ordinals, *in*: A. S. Kechris, D. A. Martin, J. R. Steel (eds.), *Cabal Seminar 81–85, Proceedings, Caltech–UCLA Logic Seminar 1981–85* [Lecture Notes in Mathematics 1333], p. 117–220
- [Ja99] Steve **Jackson**, A Survey of low level $\mathbf{L}(\mathbb{R})$ combinatorics, slides of a talk at the AMS Western Sectional Meeting at UNLV, Las Vegas NV, April 1999
- [Ja ∞] Steve **Jackson**, A Computation of δ_5^1 , *submitted to* Journal of the American Mathematical Society
- [JaKh ∞] Steve **Jackson**, Farid T. **Khafizov**, Descriptions and Cardinals below δ_5^1 , *to appear in* Journal of Symbolic Logic
- [Ka94] Akihiro **Kanamori**, *The Higher Infinite, Large Cardinals in Set Theory from Their Beginnings*, Berlin 1994 [Perspectives in Mathematical Logic]
- [Ke78] Alexander S. **Kechris**, AD and Projective Ordinals, *in*: A. S. Kechris, Y. N. Moschovakis, *Cabal Seminar 76–77, Proceedings, Caltech–UCLA Logic Seminar 1976–77*, Berlin 1978 [Lecture Notes in Mathematics 689], p. 91–132

- [KeMo78] Alexander S. **Kechris**, Yiannis N. **Moschovakis**, Appendix: The Victoria Delfino Problems, *in*: A. S. Kechris, Y. N. Moschovakis, Cabal Seminar 76–77, Proceedings, Caltech–UCLA Logic Seminar 1976–77, Berlin 1978 [Lecture Notes in Mathematics 689], p. 279–282
- [Kl77] Eugene M. **Kleinberg**, Infinitary Combinatorics and the Axiom of Determinateness, Berlin 1977 [Lecture Notes in Mathematics 612]
- [Sch99] Ute **Schmid**, Partitionskardinalzahlen und Unendliche Spiele, Wissenschaftliche Arbeit, Eberhard–Karls–Universität Tübingen 1999

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