

PROPERTIES OF THE JUMP CLASSES

ANDREW E.M. LEWIS

1. INTRODUCTION

On the Turing degree structure we consider an ordering relation, which is that inherited by the Turing reducibility on sets of natural numbers, and also the jump function, which arises naturally as the function on degrees induced by the operator which takes each set to its halting problem. In order to understand the structure it seems a basic task to understand the relationship between these two objects. The aim of this paper is to advocate a line of research which looks to better understand this relationship by establishing the order theoretic properties of degrees in each of the various jump classes. We shall survey a range of results in the area and detail a number of open questions. Some of these questions have been noted in the existing literature, while many seem not to have been previously addressed and may well be amenable to attack by known techniques.

For the degrees below $\mathbf{0}'$, the jump hierarchy was originally introduced by Cooper in [BC] and Soare in [RS].

Definition 1.1. A degree $\mathbf{a} \leq \mathbf{0}'$ is *low_n* if $\mathbf{a}^{(n)} = \mathbf{0}^{(n)}$, where $\mathbf{a}^{(n)}$ is the n th jump of \mathbf{a} . A degree $\mathbf{a} \leq \mathbf{0}'$ is *high_n* if $\mathbf{a}^{(n)} = \mathbf{0}^{(n+1)}$.

Since the jump function is order preserving, being low_n, or being high_n, may be seen to formalize being close to $\mathbf{0}$ on the one hand, or close to $\mathbf{0}'$ on the other. As originally suggested by Jockusch and Posner [JP], these notions can then be appropriately adapted to deal with degrees which are not necessarily below $\mathbf{0}'$.

Definition 1.2. For $n \geq 1$, a degree \mathbf{a} is *generalized low_n* (GL_n) if $\mathbf{a}^{(n)} = (\mathbf{a} \vee \mathbf{0}')^{(n-1)}$. A degree \mathbf{a} is *generalized high_n* (GH_n) if $\mathbf{a}^{(n)} = (\mathbf{a} \vee \mathbf{0}')^{(n)}$.

Note that these two hierarchies coincide below $\mathbf{0}'$. A notable feature of the generalized jump classes, however, is that they do not respect the ordering relation on the Turing degrees in the way that one might initially expect. Every generalized high (GH₁) that is not above $\mathbf{0}'$, for example, is bounded by a generalized low (GL₁) – this is easily seen by relativizing, to any such generalized high, the proof that every non-zero degree below $\mathbf{0}'$ can be joined to $\mathbf{0}'$ by a low degree. In most cases, however, the definition given does seem to be the correct one for dealing with degrees outside the local structures; results that hold for the high degrees, or high₂ degrees, or degrees which are not low₂, for example, can very often be modified in order to work for the respective generalized jump classes. For our purposes here, the order theoretic quirk of the generalized jump classes noted above, is probably most fruitfully seen as a feature of the Turing degrees rather than an inadequacy

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in the definition.

In what follows, we shall consider various order theoretic properties, such as the *cupping* property, the *join* property, and so on (all of which will subsequently be defined), and we shall look to establish for which jump classes it is the case that membership either ensures satisfaction or ensures failure of the property. One motivation here is quite simply that there are many basic open questions along these lines, the answers to which will tell us a lot about the Turing degree structure. Further motivation is provided by our desire for natural definability results. For all jump classes other than low, we know thanks to Nies, Shore and Slaman [NSS], that these jump classes are definable. With these results established through the use of coding techniques, however, so far there is a conspicuous lack of *natural* definability results for the jump classes. Roughly speaking, by a natural definition for a jump class, we mean a simple order theoretic property (i.e. not too long and without too many alternations of quantifiers) which is satisfied by a degree iff it belongs to that jump class. Results of this kind have long been sought by researchers in the area. The basic idea, then, is that we shall start by considering very simple order theoretic properties, and then work our way up to considering properties which are more complex – the hope is that at some point during this process, definability results will precipitate out.

Notation and terminology will be standard unless explicitly stated otherwise, and will generally follow [BC2] and [RS2].

2. THE CUPPING PROPERTY

We begin by considering a very simple property, for which the relationship with the jump classes is already well understood.

Definition 2.1. A degree \mathbf{a} satisfies the cupping property if, for all $\mathbf{b} \geq \mathbf{a}$, there exists $\mathbf{c} < \mathbf{b}$ with $\mathbf{a} \vee \mathbf{c} = \mathbf{b}$.

Theorem 2.2 (Jockusch, Posner [JP]). *All non-GL₂ degrees satisfy the cupping property.*

On the other hand, initial segment results show that there are degrees which are low, and also degrees which are low₂ non-low, which do not satisfy the cupping property (see [ML] for a thorough survey of initial segment results). Recall that a degree is PA if it contains a set which effectively codes a complete and consistent extension of Peano Arithmetic.

Theorem 2.3 (Kučera [AK]). *All PA degrees satisfy the cupping property.*

For another interesting proof of this theorem, see [AL]. By the low basis theorem [JS], there are PA degrees which are low, and since the PA degrees are upward closed, it follows that there are PA degrees which are low₂ non-low. To summarize, then, while all non-GL₂ degrees satisfy the cupping property, being low or being low₂ non-low, does not suffice to ensure either satisfaction or failure of the property.

While these observations complete the picture as far as interactions with the jump classes are concerned, we detail below some basic open questions concerning the cupping property which remain.

Definition 2.4. A degree \mathbf{b} is a *strong minimal cover* for \mathbf{a} if the degrees strictly below \mathbf{b} are precisely those below and including \mathbf{a} .

Question 2.5. Does every degree either satisfy the cupping property or have a strong minimal cover?

There is another interesting question, which concerns characterizing those degrees which satisfy the cupping property.

Definition 2.6. For $i \in \{0, 1\}$ let $\bar{i} = 1 - i$. We say $T : 2^{<\omega} \rightarrow 2^{<\omega}$ is a *tree* if, whenever $T(\sigma * i) \downarrow$ for $i \in \{0, 1\}$:

- (i) $T(\sigma) \downarrow \subset T(\sigma * \bar{i}) \downarrow$ and;
- (ii) $T(\sigma * i)$ and $T(\sigma * \bar{i})$ are incompatible.

Following the standard abuse of notation, we say $\sigma \in T$ when σ is in the range of T . A is a path through T if infinitely many initial segments of A are in T . We say a tree T is *perfect* if it is a total function, and is *\mathbf{a} -incapable* if no path through T is of degree $\geq \mathbf{a}$.

It is not difficult to see that if there is a perfect \mathbf{a} -incapable tree T of degree $\leq \mathbf{a}$, then \mathbf{a} satisfies the cupping property. Let A be of degree \mathbf{a} , and let B be of degree above \mathbf{a} . Then consider $C \leq_T B$ which is $\bigcup_i T(B \upharpoonright i)$. Since T is \mathbf{a} -incapable it follows that $C <_T B$. Given T and C we can compute B , so that $B \equiv_T A \oplus C$.

Recall that a degree is a.n.r. (array non-recursive) if, for every $f <_{wtt} K$, there exists g of degree \mathbf{a} which is not dominated by f . Note that all non- GL_2 degrees are a.n.r. and in [DJS] it is observed that many properties that hold of all non- GL_2 degrees can be shown to hold also for the a.n.r. degrees. In particular, they show that the a.n.r. degrees satisfy the cupping property and in [AL2] it is shown that if \mathbf{a} is a.n.r. then it computes a perfect \mathbf{a} -incapable tree. As noted above, Kučera showed that all PA degrees satisfy the cupping property, and in [AL] it is shown that if \mathbf{a} is PA then it computes a perfect \mathbf{a} -incapable tree. The following question therefore seems reasonable:

Question 2.7. Are the degrees which satisfy the cupping property precisely those degrees \mathbf{a} which compute perfect \mathbf{a} -incapable trees?

A positive answer to this question would suffice to show that no minimal degree satisfies the cupping property. This follows since every perfect tree of minimal degree has a path which computes the tree [AL3].

3. THE JOIN PROPERTY

We turn now to a property, which is richer in this context, essentially because it is not upward closed.

Definition 3.1. A degree \mathbf{a} satisfies the join property if, for all non-zero $\mathbf{b} < \mathbf{a}$ there exists $\mathbf{c} < \mathbf{a}$ with $\mathbf{b} \vee \mathbf{c} = \mathbf{a}$.

The strongest result here is as follows:

Theorem 3.2 (Downey, Greenberg, Lewis, Montalbán, [DGLM]). *All degrees which are non- GL_2 satisfy the join property.*

Initial segment results can be used in order to show that all possibilities can be realized for the low and for the low_2 non-low degrees, i.e. there exist low degrees which satisfy the join property and low degrees that don't, and similarly for the degrees which are low_2 non-low.

The situation becomes more interesting, however, when we consider the upward closure – for which degrees is it the case that all degrees above satisfy the join property? In looking to answer this question, it becomes natural to consider upward closed classes of degrees which we are used to working with. Do all PA degrees satisfy the join property? Do all a.n.r. degrees satisfy the join property? Another natural question is as to whether satisfaction of the cupping property is equivalent to all degrees above satisfying join. We can answer all of these questions with the following result:

Definition 3.3. A function $f : \omega \rightarrow \omega$ is fixed-point-free if, for all n , $\phi_n \neq \phi_{f(n)}$, where ϕ_n is the n th partial computable function in some fixed effective listing of all such functions. A degree is fixed-point-free if it contains a function which is fixed-point-free.

Theorem 3.4 (Lewis [AL4]). *All low fixed-point-free degrees fail to satisfy the join property.*

Corollary 3.5. Above each low degree, there is a low degree which doesn't satisfy join.

Proof. Each low degree is bounded by a degree which is low and fixed-point-free. \square

Corollary 3.6. There are PA/a.n.r./Martin-Löf random degrees which don't satisfy join.

Proof. All PA degrees and all Martin-Löf random degrees are fixed-point-free, and it follows from the low basis theorem that there exist PA degrees which are low and also Martin-Löf random degrees are low. For the a.n.r. degrees, the corollary follows from Corollary 3.5 and the fact that the a.n.r. degrees are upward closed. \square

For an introduction to the study of algorithmic randomness (and, in particular, Martin-Löf randomness), we refer the reader to [AN] and [DH].

Corollary 3.7. Satisfaction of the cupping property is not equivalent to all degrees above satisfying join.

Proof. Any PA degree properly bounds another PA degree. The result then follows from Corollary 3.6 and the fact that all PA degrees satisfy the cupping property. \square

There is another theorem along the same lines:

Theorem 3.8 (Lewis [AL4]). *Above every low c.e. degree, there is a low c.e. degree which doesn't satisfy join.*

This leaves open various questions. Working below $\mathbf{0}'$ first of all, we have already managed to separate the non- low_2 degrees from the low degrees, and it seems natural to ask if this can be extended to give a definition of low_2 :

Question 3.9. In $\mathcal{D}[\leq \mathbf{0}']$, are the low_2 degrees precisely those for which it is not the case that all degrees above satisfy join?

It remains open, in fact, whether $\mathbf{0}'$ can be given an extremely simple definition using the join property, although one would expect the following question to be answered in the negative:

Question 3.10. Can $\mathbf{0}'$ be defined as the least degree such that all degrees above satisfy join?

There is an interesting observation to be had here. Let us suppose for a moment that question 3.10 receives a negative response, and that, in fact, any degree which bounds a high degree satisfies join. This moves us towards a definition of $\mathbf{0}'$ in another direction. Immediately from this we get a formula sufficient to distinguish $\mathbf{0}'$ from all degrees comparable with it, because then all degrees above $\mathbf{0}'$ satisfy the following formula, while no degree strictly below $\mathbf{0}'$ does so:

\mathbf{a} satisfies mincup, and $\forall \mathbf{b} \geq \mathbf{a}, \forall$ minimal degrees $\mathbf{m} < \mathbf{b}, \mathbf{b}$ satisfies $\text{join}(\mathbf{m})$,

where \mathbf{a} satisfies mincup if for all $\mathbf{b} \geq \mathbf{a}$ there exists a minimal degree $\mathbf{m} < \mathbf{b}$ with $\mathbf{a} \vee \mathbf{m} = \mathbf{b}$, and where $\text{join}(\mathbf{m})$ means join above \mathbf{m} , i.e. \mathbf{b} satisfies $\text{join}(\mathbf{m})$ if, for all \mathbf{c} with $\mathbf{m} < \mathbf{c} < \mathbf{b}$ there exists \mathbf{d} with $\mathbf{m} < \mathbf{d} < \mathbf{b}$ and $\mathbf{d} \vee \mathbf{c} = \mathbf{b}$. Let us see first why degrees above $\mathbf{0}'$ satisfy the formula above. All such degrees satisfy mincup – this follows from the fact that \emptyset' computes a perfect tree of sets of minimal degree. If $\mathbf{b} \geq \mathbf{0}'$ bounds a minimal degree \mathbf{m} then, since all minimal degrees are GL_2 , \mathbf{b} bounds a degree which is high relative to \mathbf{m} and so satisfies $\text{join}(\mathbf{m})$ according to our hypothesis (given relativization).

Now suppose that $\mathbf{a} < \mathbf{0}'$. Then \mathbf{a} may not satisfy mincup, but if it does then let $\mathbf{b} \geq \mathbf{a}$ be GL_1 (such a degree will exist, since any degree which is not above $\mathbf{0}'$ is bounded by a degree which is generalized low), and let \mathbf{m} be a minimal degree such that $\mathbf{m} \vee \mathbf{a} = \mathbf{b}$. Then $\mathbf{m} \vee \mathbf{0}' \geq \mathbf{b} \vee \mathbf{0}' = \mathbf{b}'$, so $\mathbf{m} \vee \mathbf{0}' = \mathbf{b} \vee \mathbf{0}' = \mathbf{b}' = \mathbf{m}'$, so that \mathbf{b} is actually low over \mathbf{m} . By Corollary 3.5, above every low degree there exists a low degree which doesn't satisfy join. This proof relativizes, meaning that we may choose $\mathbf{c} \geq \mathbf{b}$ which doesn't satisfy $\text{join}(\mathbf{m})$.

One may reasonably ask how useful this observation actually is, given that we are supposing something that may well not be true – it could well be the case that there are degrees which bound a high degree and which do not satisfy the join property. The point here, though, is that we don't have to consider just the join property. Any property which suffices to separate high and low cones will suffice:

Question 3.11. Can we find a natural order theoretic property P , which suffices to separate the high and low cones, in the sense that above any low degree there is a degree which does not satisfy P , while any degree which bounds a high degree satisfies P ?

Question 3.12. If $\mathbf{a} \not\geq \mathbf{0}'$ does there necessarily exist $\mathbf{b} \geq \mathbf{a}$ and a minimal degree $\mathbf{m} < \mathbf{b}$ such that \mathbf{b} is low over \mathbf{m} ?

These two questions are interesting because positive answers to both would give a natural definition of the jump (presuming necessary relativizations hold). This follows because then $\mathbf{0}'$ would be the least degree such that:

$$\forall \mathbf{b} \geq \mathbf{a}, \forall \text{ minimal degrees } \mathbf{m} < \mathbf{b}, \mathbf{b} \in P(\mathbf{m}),$$

where $P(\mathbf{m})$ denotes P above \mathbf{m} , in just the same way that we let $\text{join}(\mathbf{m})$ denote join above \mathbf{m} previously.

4. THE JOIN OF MINIMALS PROPERTY

Another basic question is as to which degrees satisfy the property of bounding a minimal degree. The strongest result here is due to Jockusch, who extended the result of Cooper that every high degree bounds a minimal degree:

Theorem 4.1 (Jockusch [CJ]). *Every generalized high degree bounds a minimal degree.*

The fact that this is sharp, follows from a difficult result of Lerman's:

Theorem 4.2 (Lerman [ML2]). *There exists a high_2 degree which does not bound any minimal degree.*

We consider next those degrees which are the join of two minimal degrees. The strongest result here is:

Theorem 4.3 (Ellison, Lewis [EL]). *All GH_1 degrees are the join of two minimal degrees.*

This settles a conjecture of Posner's from the 70s. The previous results were as follows. First Cooper showed that $\mathbf{0}'$ is the join of two minimal degrees [BC3], and then Posner [DP] extended this to all degrees above $\mathbf{0}'$. It follows from Theorem 4.2 that Theorem 4.3 is sharp in terms of the jump hierarchy.

Posner asked, in fact, whether $\mathbf{0}'$ could be defined as the least degree such that all degrees above are the join of two minimal degrees. This was answered by Shore [SH] who showed that there exists a degree incomparable with $\mathbf{0}'$ such that all degrees above are the join of two minimal degrees. This immediately gives members of each generalized jump class which are the join of two minimal degrees. The following question remains open:

Question 4.4. Is $\mathbf{0}'$ minimal amongst the degrees such that all degrees above are the join of two minimal degrees?

5. THE MINIMAL CUPPING PROPERTY

We gave the definition earlier:

Definition 5.1. A degree \mathbf{a} satisfies the minimal cupping property (mincup) if for all $\mathbf{b} \geq \mathbf{a}$ there exists a minimal degree $\mathbf{m} < \mathbf{b}$ with $\mathbf{a} \vee \mathbf{m} = \mathbf{b}$.

Let us consider the situation below $\mathbf{0}'$ first.

Proposition 5.2. In $\mathcal{D}[\leq \mathbf{0}']$, all high degrees satisfy the minimal cupping property.

Proof. We give only a sketch of the proof, for those familiar with minimal degree constructions.

Suppose given $A \leq_T B$ which are both of high degree. We must construct $C \leq_T B$ such that $A \oplus C \equiv_T B$ and C is of minimal degree. To do so, apply Jockusch's use of the recursion theorem for building a minimal degree below a high degree [CJ] in order to construct C which is computable in B , but this time, since A is high, suppose that the function which approximates whether every initial

segment of C has Ψ -splittings above it in any given splitting tree, is computable in A . At the end of each stage $s + 1$ we code $B(s)$ with our choice as to whether our next initial segment of C should be the leftmost or the rightmost string in the splitting found at that stage. $A \oplus C$ can retrace the construction and so compute B . □

This result is clearly sharp in terms of the jump hierarchy – again this follows from Lerman’s result [ML2] that there exist high_2 degrees which don’t bound minimal degrees. There is a lot more to be said here though:

Theorem 5.3 (Ellison, Lewis [EL2]). *In $\mathcal{D}[\leq \mathbf{0}']$, a c.e. degree is high iff it satisfies the minimal cupping property.*

This gives us a nice characterization of the high c.e. degrees (and gives a natural definition of the high c.e. degrees in terms of a definition for the c.e. degrees in $\mathcal{D}[\leq \mathbf{0}']$). Unfortunately the result can’t be extended to give us a natural definition of the high degrees:

Theorem 5.4 (Ellison, Lewis [EL2]). *There exists a low degree which satisfies the minimal cupping property.*

Note that this theorem holds globally. The first remaining questions here, also concern the global structure.

Question 5.5. Do all GH_1 degrees satisfy mincup?

6. THE MEET AND COMPLEMENTATION PROPERTIES

We consider next, the meet and complementation properties:

Definition 6.1. A degree \mathbf{a} satisfies the meet property if, for all $\mathbf{b} < \mathbf{a}$, there exists non-zero $\mathbf{c} < \mathbf{a}$ such that $\mathbf{b} \wedge \mathbf{c} = \mathbf{0}$.

Definition 6.2. A degree \mathbf{a} satisfies the complementation property if, for all non-zero $\mathbf{b} < \mathbf{a}$, there exists $\mathbf{c} < \mathbf{a}$ such that $\mathbf{b} \wedge \mathbf{c} = \mathbf{0}$ and $\mathbf{b} \vee \mathbf{c} = \mathbf{a}$.

First of all, let us establish the uninteresting cases – initial segment results can be used in order to show that all possibilities can be realized for the low and for the low_2 non-low degrees. On the positive side, Posner [DP2] showed that $\mathbf{0}'$ satisfies the complementation property using a non-uniform proof. This non-uniformity was subsequently shown not to be necessary by Slaman and Steel [SS]. The following is the strongest result known:

Theorem 6.3 (Greenberg, Montalbán and Shore [GMS]). *All generalized high degrees satisfy the complementation property.*

The proof given for this stronger result is once again non-uniform, and it remains open as to whether the complement here can be constructed uniformly. For all other jump classes, interaction with these two properties remains open:

Question 6.4. Do all non- GL_2 satisfy complementation/meet? All GH_2 ?

We would conjecture that there exists a high_2 degree which doesn’t satisfy the meet property, so that these questions all receive a negative answer. At the time of writing, we are examining a potential proof of the following result:

Conjecture 6.5 (Lewis, Ng). *All c.e. degrees satisfy the meet property i.e. if \mathbf{a} is c.e. then for all $\mathbf{b} < \mathbf{a}$, there exists non-zero $\mathbf{c} < \mathbf{a}$ (which is not necessarily c.e.) such that $\mathbf{b} \wedge \mathbf{c} = \mathbf{0}$.*

A positive solution to this question would settle a conjecture of Cooper's from the 80s. The following question was asked by Slaman and Steel:

Question 6.6 (Slaman, Steel [SS]). Can $\mathbf{0}'$ be defined as the least degree such that all degrees above satisfy complementation?

As with Question 3.10, the expectation is presumably that this question will eventually be answered in the negative, but that the counter example may be difficult to construct.

7. THE CAPPING PROPERTY

In this section, we briefly consider a property about which little is known:

Definition 7.1. A degree \mathbf{a} satisfies the capping property if, for all $\mathbf{b} > \mathbf{a}$ there exists non-zero $\mathbf{c} < \mathbf{b}$ such that $\mathbf{a} \wedge \mathbf{c} = \mathbf{0}$.

It follows from Theorem 5.4, that there exists a low degree such that all degrees above satisfy the capping property. This suffices to show that there exist members of each jump class which satisfy the capping property. It also follows from Proposition 5.2 that, in $\mathcal{D}[\leq \mathbf{0}']$, all high degrees satisfy the capping property. Nothing else substantial is known at this point.

Question 7.2. Do all GH_1 degrees satisfy the capping property?

8. THE MINIMAL COMPLEMENTATION PROPERTY

In this final section, we consider the most complex property so far:

Definition 8.1. A degree \mathbf{a} satisfies the minimal complementation property if, for all non-zero $\mathbf{b} < \mathbf{a}$, there exists a minimal degree $\mathbf{m} < \mathbf{a}$ such that $\mathbf{b} \vee \mathbf{m} = \mathbf{a}$.

The results here are as follows:

Theorem 8.2 (Lewis, Seetapun, Slaman [AL5]). *$\mathbf{0}'$ satisfies the minimal complementation property.*

Theorem 8.3 (Lewis [AL6]). *All degrees above $\mathbf{0}'$ satisfy the minimal complementation property.*

In fact, one can complement quite a lot of degrees simultaneously:

Theorem 8.4 (Lewis [AL7]). *There exists a minimal degree below $\mathbf{0}'$ which complements all (non-zero, incomplete) c.e. degrees.*

While it is immediately clear that no Δ_2^0 degree can complement all other non-zero and incomplete Δ_2^0 degrees, one might hope that *some* version of this theorem might hold for the Δ_2^0 degrees in general – there might be two degrees such that each non-zero, incomplete degree is complemented by at least one of them, for example. In fact, however, this fails very strongly:

Theorem 8.5 (Lewis [AL8]). *For every degree \mathbf{c} with $\mathbf{0} < \mathbf{c} \leq \mathbf{0}'$ and every uniformly Δ_2^0 sequence of degrees $\{\mathbf{b}_i\}_{i \geq 0}$ such that, for all i , $\mathbf{b}_i \not\leq \mathbf{c}$, there exists \mathbf{a} with $\mathbf{0} < \mathbf{a} < \mathbf{0}'$ such that $\mathbf{a} \vee \mathbf{b}_i \not\leq \mathbf{c}$ for all i .*

The first remaining questions are these:

Question 8.6. Do all/any incomplete high degrees satisfy the minimal complementation property?

Question 8.7. Can $0'$ be defined as the least degree such that all degrees above satisfy minimal complementation?

9. FINAL COMMENTS

Our aim here has been to present the case that this is an area of research in which many basic and fundamental questions remain open. While we are yet to establish any natural definability results for the jump classes, the number of simple order theoretic properties for which interactions with the jump classes are not yet well understood, would certainly seem to leave open the realistic possibility of finding results of this kind.

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PURE MATHEMATICS, UNIVERSITY OF LEEDS, ENGLAND, LS29JT
E-mail address: andy@aemlewis.co.uk