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On Low for Speed Oracles

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Abstract

Relativizing computations of Turing machines to an oracle is a central concept in the theory of computation, both in complexity theory and in computability theory(!). Inspired by lowness notions from computability theory, Allender introduced the concept of “low for speed” oracles. An oracle A is low for speed if relativizing to A has essentially no effect on computational complexity, meaning that if a decidable language can be decided in time $f(n)$ with access to oracle A , then it can be decided in time $\text{poly}(f(n))$ without any oracle. The existence of non-computable such A 's was later proven by Bayer and Slaman, who even constructed a computably enumerable one, and exhibited a number of properties of these oracles as well as interesting connections with computability theory. In this paper, we pursue this line of research, answering the questions left by Bayer and Slaman and give further evidence that the structure of the class of low for speed oracles is a very rich one.

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1 Introduction

The subject of this paper is oracle computation, more specifically the effect of oracles on the speed of computation. There are many notable results about oracles in classical complexity, beginning with the Baker-Gill-Solovay result [3] which asserts that there are oracles A such that $P^A = NP^A$, but that there are also oracles B such that $P^B \neq NP^B$ (thus demonstrating that methods that relativize will not suffice to solve basic questions like P vs NP). An underlying question is whether oracle results can say things about complexity questions in the unrelativized world. Eric Allender and his co-authors [1, 2] showed that oracle access to the sets of random strings could give insight into basic complexity questions. For example,



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in [2], Allender et. al. showed that $\cap_U \mathbf{P}^{R_{K_U}} \cap \mathbf{COMP} \subseteq \mathbf{PSPACE}$ where R_{K_U} denotes the strings whose prefix-free Kolmogorov complexity (relative to universal machine U) is at least their length, and \mathbf{COMP} denotes the collection of computable sets. Later the “ $\cap \mathbf{COMP}$ ” was removed by Cai et. al. [7]. Thus we conclude that reductions to very complex sets like the random strings somehow gives insight into very simple things like computable sets.

Inspired by lowness notions in computability theory, Allender asked whether there were non-trivial sets which were “low for speed” in that, as oracles, they did not accelerate running times of computations by more than a polynomial amount. Of course, as stated this makes little sense since using any X as oracle, we can decide membership in X in linear time, while without oracle X may not even be computable at all! Thus, what we are really interested in is the set of oracles which do not speed-up the computation of *computable sets* by more than a polynomial amount. More precisely, an oracle X is *low for speed* if for any computable language L , if some Turing machine M with access to oracle X decides L in time f , then there is a Turing machine M' without oracle and polynomial p such that M' decides L in time $p \circ f$. (Here computation time of oracle computation is counted in the usual complexity-theoretic fashion: we have a “query tape” on which we can write strings, and once a string x is written on this tape, we get to ask the oracle whether x belongs to it in time $O(1)$).

There are trivial examples of such sets, namely oracles that belong to \mathbf{P} , because any query to such an oracle can be replaced by a polynomial-time computation. Allender’s precise question was therefore:

Is there an oracle $X \notin \mathbf{P}$ which is low for speed?

Such an X , if it exists, has to be non-computable, for the same reason as above (if X is computable and low for speed, then X is decidable in linear time using oracle X , thus – by lowness – decidable in polynomial time without oracle, i.e., $X \in \mathbf{P}$).

A partial answer was given by Lance Fortnow (unpublished), who observed the following.

► **Theorem 1** (Fortnow). *If X is a hypersimple and computably enumerable oracle, then X is low for polynomial time, in that if $L \in \mathbf{P}^X$, then $L \in \mathbf{P}$.*

Allender’s question was finally solved by Bayer and Slaman, who showed the following.

► **Theorem 2** (Bayer-Slaman [4]). *There are non-computable, computably enumerable, sets X which are low for speed.*

Once their existence is established, it is natural to wonder what kind of sets might be low for speed. A precise characterization seems currently out of reach, but it is interesting to see how lowness for speed interacts with other computability-theoretic properties. One needs however to keep in mind that lowness for speed is *not* closed under Turing equivalence: we saw above that in the $\mathbf{0}$ degree (computable sets) some members are low for speed and others that are not (on the other hand it is easy to see that if A is polynomial-time reducible to B and B is low for speed, then A is also low for speed).

In his PhD thesis, Bayer showed that if X is computably enumerable and of promptly simple Turing degree, then X is *not* low for speed, but also proved that this did not characterize the computable enumerable oracles that are low for speed. Bayer also studied the size of the set of low for speed oracles, where ‘size’ is understood in terms of Baire category. Surprisingly, whether the set of low for speed oracles is meager or co-meager depends on the answer of the famous $\mathbf{P} = ? \mathbf{NP}$ question.

In this paper, we continue Bayer and Slaman’s investigation on the set of low for speed oracles. In the next section, we give an easier proof of the existence of non-computable low

for speed oracles which does not require the full Bayer-Slaman machinery (but the oracle we construct is not computably enumerable). In Section 3, we focus on the computably enumerable low for speed oracles, and prove that – quite surprisingly – they cannot be low in the computability-theoretic sense, but can however be low_2 . Finally, we pursue Bayer and Slaman’s idea to study how large the set of low for speed oracles is, in terms of measure and category. In particular, we solve a question they left open by showing that the set of low for speed oracles has measure 0 and obtain some interesting connections with algorithmic randomness. Finally, though lowness for speed is not closed under Turing equivalence, it is nonetheless natural to ask which Turing degrees contain a low for speed member, which is what Section 5 is about.

Throughout this paper, we will denote by $\{0, 1\}^*$ the set of finite strings. In our setting, an oracle is a *language*, i.e., a subset of $\{0, 1\}^*$; however, as is typical in computability theory, it is more convenient in some of the results we present below to view oracles as infinite binary sequences (whose set we denote by $\{0, 1\}^\omega$), by first identifying finite strings with integers (the $(n + 1)$ -th string in the length-lexicographic order being identified with n) making the oracle a subset of \mathbb{N} and then identifying the oracle with its characteristic sequence (the $(n + 1)$ -th bit is 1 if n belongs to the oracle, 0 otherwise). When building oracles X with certain computability-theoretic properties, viewed as infinite binary sequences, we will often need to refer to prefixes of X , which are themselves binary strings. To avoid confusion between *members* and *prefixes* of oracles, we will use latin letters x, y, z, \dots to denote members of oracles, and greek letters σ, τ, \dots for prefixes of oracles. Two strings σ and τ are *incompatible* if for some $i < \min(|\sigma|, |\tau|)$, $\sigma(i) \neq \tau(i)$. We denote this by $\sigma \perp \tau$. The join $X \oplus Y$ of two infinite binary sequences X, Y is the sequence $X(0)Y(0)X(1)Y(1)\dots$. Finally $X \upharpoonright n$ is the prefix of X of length n .

Our paper requires some knowledge of computability theory and algorithmic randomness. One can consult the book [8] for the results and concepts we allude to below. Our notation is mostly standard. We fix a computable bijection $\langle \cdot, \cdot \rangle$ from pairs of strings/integers to strings/integers. We also fix an effective list (Φ_e) of all oracle Turing functionals (or machines: Φ_e^A is the Turing machine of index e with oracle A , which for a fixed A is a partial function from $\{0, 1\}^*$ to $\{0, 1\}$). For a given functional Φ_e and oracle A , $\text{time}(\Phi_e^A, x)$ denotes the running time of Φ_e on input x with oracle A (counting time according to the model of computation described above) and $\text{time}(\Phi_e^A)$ is the function $x \mapsto \text{time}(\Phi_e^A, x)$. We let (R_i) be an effective enumeration of all partial computable functions from $\{0, 1\}^*$ to $\{0, 1\}$. We denote the set of low for speed oracles by LFS , and the subset of LFS consisting of its non-computable elements by LFS^* .

Due to space restrictions some proofs are omitted. They can be found in the extended version of the paper, available at <https://arxiv.org/abs/1712.09710>.

2 Existence of non-computable low for speed sets

In this section we will present a simple proof of the existence of a non-computable low for speed oracle. Define the set S of strings by $S = \{0^{2^n} \mid n \in \mathbb{N}\}$ and – identifying S with a set of integers as discussed above – let \mathbb{S} be the set of ‘sparse’ infinite binary sequences (viewed as sets of integers) that only contain elements from S , that is, $\mathbb{S} = \{X \in \{0, 1\}^\omega \mid X \subseteq S\}$.

By extension, we say that a string σ is in \mathbb{S} if it is a prefix of some element of \mathbb{S} . The interest of the set \mathbb{S} is that there are only $O(n)$ strings in \mathbb{S} of length n . Thus, given a Turing machine Φ , it is possible to simulate in time $\text{poly}(t)$ the behaviour of Φ^X during t steps of computation on all $X \in \mathbb{S}$ (an idea that is already present in the Bayer-Slaman argument presented in the next section).

► **Theorem 3.** *There exists a non-computable X which is low for speed.*

Proof. We want X to satisfy all requirements $\mathcal{R}_{(e,i)}$, defined as follows:

$\mathcal{R}_{(e,i)}$: either R_i is partial, or $\Phi_e^X \neq R_i$, or $\Phi_e^X = R_i$ but the computation of R_i via Φ_e^X can be simulated by a functional Ψ running in time polynomial in $\text{time}(\Phi_e^X)$.

We build our oracle X by finite extension. Let σ_0 be the empty string. At stage $s + 1 = \langle e, i \rangle$, do the following.

- (a) If there is an n and a $\tau \in \mathbb{S}$ extending σ_s such that $\Phi_e^\tau(n)$ and $R_i(n)$ both converge and have different values, then let σ_{s+1} be the first (say in length-lexicographic order) such string τ .
- (b) If there is no such string τ , then take $\sigma_{s+1} = \sigma_s 0$

Finally let X be the unique infinite sequence extending all σ_s . We claim that X is as wanted. Let us first prove that X must be incomputable. Suppose $X = R_i$ for a total R_i . Let e be an index such that Φ_e is the identity functional. By construction, when choosing the prefix τ of X at stage $s + 1 = \langle e, i \rangle$, we must be in case (a), and thus τ is precisely chosen to ensure $X \neq R_i$, a contradiction. Let us now prove that X is low for speed. Fix a pair (e, i) let $s + 1 = \langle e, i \rangle$, and let us see how σ_{s+1} was constructed. If we were in case (a) at that stage, we have ensured $\Phi_e^{\sigma_{s+1}} \perp R_i$ and thus $\Phi_e^X \perp R_i$, thereby satisfying $\mathcal{R}_{(e,i)}$. If we were in case (b), there are three subcases:

- Either R_i is partial, then the requirement $\mathcal{R}_{(e,i)}$ is satisfied.
- Or there is an n such that $\Phi_e^\tau(n) \uparrow$ for any extension τ of σ_s , in which case $\Phi_e^X(n) \uparrow$ and thus $\Phi_e^X \neq R_i$ should R_i be total.
- Or, if we are in neither of the two above cases, for every n there is an extension τ of σ_s such that $\Phi_e^\tau(n) \downarrow$, and for any such τ , we have $\Phi_e^\tau(n) = R_i(n)$. In this case, we can build a functional Ψ which computes R_i as follows. On input n , at stage t , it computes $\Phi_e^\tau(n)$ during t steps of computation for all $\tau \in \mathbb{S}$ of length t extending σ_s . If a τ is found such that $\Phi_e^\tau(n) \downarrow$, then we set $\Psi(n) = \Phi_e^\tau(n)$. As we already mentioned, there are only $O(t)$ strings of length t in \mathbb{S} and it is obvious that they can be listed in polynomial time. Hence, simulating all computations $\Phi_e^\tau(n)$ during t steps can be done in time $p(t)$ for some polynomial t . This shows that for any $Y \in \mathbb{S}$ extending σ_s , if $\Phi_e^Y(n)$ returns (the value of $R_i(n)$) in time t , this is found out by the procedure Ψ at stage t , which corresponds to $\sum_{s \leq t} p(s) + O(1)$ steps of computation for Ψ , which is also polynomial in t . This being true for any $Y \in \mathbb{S}$ extending σ_s , we have in particular that $\text{time}(\Psi) = \text{poly}(\text{time}(\Phi_e^X))$. ◀

One should note that the case disjunction in this proof is a Σ_1/Π_1 dichotomy, and therefore one can carry out the construction below $\mathbf{0}'$, therefore establishing the existence of a $\mathbf{0}'$ -computable set that is low for speed. This is weaker than the Bayer-Slaman result presented in the next section, which asserts the existence of a *c.e.* such set. However, this proof is both simpler and, as we will see in the remainder of the paper, has further useful corollaries.

3 Computationally enumerable low for speed sets

We now restrict ourselves to the computably enumerable (c.e.) sets, and study which of these can be low for speed. For the sake of completeness, we present the main ideas of the proof of Bayer and Slaman [4] that there are indeed c.e. sets in LFS^* .

► **Theorem 4** (Bayer-Slaman Theorem). *There exist c.e. non-computable sets that are low for speed.*

Proof sketch. The proof uses a tree-of-strategies argument. We need to satisfy

$$\mathcal{P}_e : \bar{A} \neq W_e,$$

and

$$\mathcal{L}_{e,i} : \text{If } \Phi_e^A = R_i \text{ total, then some } \Psi \text{ computes } R_i \text{ in time polynomial in } \text{time}(\Phi_e^A).$$

The \mathcal{P}_e -strategy is a standard Friedberg-Muchnik strategy on a tree. A node ρ devoted to this requirement picks a fresh follower x , waits for $x \in W_e[s]$ and if this happens puts x into A .

The basic strategy for $\mathcal{L}_{e,i}$ is the following. First, throughout the whole construction of A , we will promise that if we add an element x to A at stage t , then we must immediately also add all $y \in [x, t]$ (this is often referred to as a *dump construction*). This way, at any stage s , there will only be at most s strings α of length s that can potentially be a prefix of (the final) A . And thus – just like in the previous section – at stage s , it is possible to emulate all computations $\Phi_e^\alpha(x)[s]$ for all such α 's and $x \leq s$ in time $\text{poly}(s)$.

When the strategy is eligible to act at stage s , for every $x \leq s$ on which Ψ is not defined yet, it computes all $\Phi_e^\alpha(x)[s]$ for all potential prefixes α of A , and should one of them converge, defines $\Psi(x)$ to be the value of $\Phi_e^\alpha(x)$ for the α that has the fastest convergence. If no $\Phi_e^\alpha(x)[s]$ converges, $\Psi(x)$ remains undefined until the strategy is eligible to act again.

Now, if at some later stage we find a value x such that $R_i(x) \downarrow$ and $\Psi(x) \neq R_i(x)$, then we find the α such that $\Psi(x) = \Phi_e^\alpha$ and add elements into A so that α becomes a prefix of A . This ensures $\Phi_e^A \neq R_i$ and terminates the strategy. All strategies of lower priorities are then injured and must be reset. If we never find such an x , this means that either Φ_e^A is partial, or R_i is, or $\Psi = \Phi_e^A = R_i$ and by construction the running time of Ψ is polynomial in the running time of Φ_e^A .¹

This is enough to ensure the success of the strategy in isolation. The difficulty comes from the interaction with lower-priority strategies which might want to add elements into A . The final key to the Bayer-Slaman proof is the following. Suppose that at some stage s a strategy of lower priority wants to add an interval $[y, s]$ of elements into A . The problem is that the computations on this configuration might be *slow*. Perhaps for some x of length $\leq s$ we have not as yet seen $\Phi_e^{A_s \cup [y, s]}(x) \downarrow$. Even more importantly, we don't even know that the value of this will agree with the value $\Psi(x)$ we have already defined.

The idea is the following. R_i has to confirm the computations, that is, we wait until $R_i(x)$ converges on all x where Ψ has already been defined. When (and if) this happens, we must have $\Psi(x) = R_i(x)$ for all such x otherwise we would be in the above case where we can ensure $\Phi_e^A \neq R_i$ and satisfy the requirement. If this never happens, our requirement will be satisfied because R_i would be partial. And if it does happen, then we can safely add $[y, s]$ to A because if this causes $\Phi_e^A(x)$ to change, it will yield $\Phi_e^A(x) \neq R_i(x)$ which satisfies the requirement. But there is one last problem: while waiting for this confirmation, the construction of Ψ cannot wait as we need it to be as fast as Φ_e^A . The crucial trick is, from the point of view of our strategy, to carry on *as if* $[y, s]$ had already been enumerated into A .

¹ Actually, there is a subtlety here: one must ensure that the strategy for $\mathcal{L}_{e,i}$ is eligible to act often enough, i.e., allowed to act for the n -th time before stage $q(n)$ for some polynomial q , but this can easily be ensured.

Indeed, if the confirmation ever happens, the elements of $[y, s]$ will be truly enumerated into A which Ψ will have correctly assumed ahead of time, and if the confirmation never happens, Ψ might be wrong (i.e., $\Psi \neq \Phi_e^A$) but this will not matter because in this case R_i will be either partial or different from Φ_e^A . Of course, in the case where the confirmation never occurs the strategy of lower priority never gets to enumerate into A the elements it wants. This is where we make use of a standard tree construction where strategies of lower priorities guess the outcome of strategies of higher priority. We refer the reader to [4] for details. ◀

Within the c.e. sets, one would expect that a low for speed c.e. set would be one with little computational power, in the same way that sets low for 1-randomness are all (super-)low (see Nies [14]). The next theorem is therefore quite surprising.

► **Theorem 5.** *If A is non-computable, c.e., and of low Turing degree (i.e. $A' \equiv_T \emptyset'$), then A is not low for speed.*

Proof. Assume that A is not computable, is c.e., and is low. Let (Φ_e, p_e) be an enumeration of pairs of one functional and one polynomial with coefficients in \mathbb{N} . We will build a Turing functional Ψ and a computable set R such that $\Psi^A = R$. This is our global requirement and we make the following global commitment: if a value $R(n)$ gets defined at some stage, $\Psi^X(n)$ is immediately defined to be equal to $R(n)$ for all X 's on which $\Psi^X(n)$ is still undefined. We want to satisfy, for each e :

$$(\mathcal{R}_e) : \Phi_e \text{ does not compute } R \text{ in time } p_e(\text{time}(\Psi^A))$$

thus proving that A is not low for speed. We give a strategy for a single requirement (\mathcal{R}_e) (the strategies for different requirements interact to the extent that each one needs to know the actions of the others in order to pick fresh witnesses, but the construction is injury-free). Throughout the construction, we build a ‘verifier’, i.e., a partial computable S such that $S(e, \cdot)$ is the attempt by the (\mathcal{R}_e) -strategy to guess A . We also define an auxiliary functional Θ common to all strategies whose index we know in advance, and use the lowness of A to obtain a computable 0-1 valued function $h(\cdot, \cdot)$ such that $\lim_t h(e, t)$ exists for all e , and equals 1 when $\Theta^A(e) \downarrow$, 0 otherwise. (Informally, $\Theta^X(e) \downarrow$ means that a prefix of X is believed to be a prefix of A at some stage of the strategy for (\mathcal{R}_e) , and this will cause the strategy to enter Case 3 as described below.)

At the initial stage s_1 , S is empty and we pick a first fresh witness w_1 larger than any integer mentioned so far in the construction and define $\Psi^{A_{s_1} \upharpoonright 1}(w_1) = 0$. Let t_1 be the time this computation takes. Now, check whether $\Phi_e(w_1)$ returns in $p_e(t_1)$ steps. We distinguish three cases:

Case 1: $\Phi_e(w_1)$ returns 1 in $\leq p_e(t_1)$ steps. In this case, we set $R(w_1) = 0$ and $R(n) = 0$ for all $n \leq w_1$ on which R is still undefined, and commit to having $\Psi^A(w_1) = 0$ even after potential future A -changes. This way we ensure $\Phi_e \neq R = \Psi^A$, thus immediately satisfying (\mathcal{R}_e) , and we stop the strategy for this requirement.

Case 2: $\Phi_e(w_1)$ returns 0 in $\leq p_e(t_1)$ steps. In this case, we do not define $R(w_1)$ just yet. Instead, we set $S(e, 1) = A_{s_1} \upharpoonright 1$. We then create a second witness w_2 at stage s_2 and proceed as above for this new witness (with $A_{s_2} \upharpoonright 2$ in place of $A_{s_1} \upharpoonright 1$). And so on: for further occurrences of this case, the procedure will extend S and create a witness w_3 at stage s_3 looking at prefixes of length $l = 3$, etc (and if Case 2 then causes a reset, we stay at the same level l , that is, keep the same l , when resetting). Meanwhile, we continue to monitor A . Again, there are two subcases for a given l :

- (a) At some point we discover that $A_{s_l} \upharpoonright l$ is not in fact an initial segment of A , we are then free to set $R(w_l) = 1$ (which will guarantee $\Psi^A(w_l) = 1 = R(w_l) \neq \Phi_e(w_l)$ since we only committed to $\Psi^\sigma(w_l) = 0$ for σ 's that are not prefixes of A), and this way we have satisfied (\mathcal{R}_e) . We then stop the strategy.
- (b) $A_{s_l} \upharpoonright l$ is a true initial segment of A , in which case nothing further will happen regarding witness w_l . What is gained is that $S(e, l)$ will be defined to be $A_{s_l} \upharpoonright l = A \upharpoonright l$, thus progress was made towards computing A .

Case 3: $\Phi_e(w_1)$ is still undefined after $p_e(t_1)$ steps. In this case, we set $\Theta^{A_{s_1} \upharpoonright 1}(e) \downarrow$ (which should be interpreted as signalling that we are currently in Case 3). Observe that if $A_{s_1} \upharpoonright 1$ is a true prefix of A , this implies $\Theta^A(e) \downarrow$ and therefore we would have $\lim h(e, t) = 1$. We distinguish two subcases.

- (a) The current value $h(e, s)$ is 0. Then we wait for a stage $t > s$ such that either $h(e, t) = 1$ or $A_t \upharpoonright 1 \neq A_s \upharpoonright 1$ (one of the two must happen as we explained above). If the former happens first we move to subcase (b) below. If the latter happens first, we restart the procedure, resetting s_1 to the current stage t and keeping the same w_1 .
- (b) The current value $h(e, s)$ is 1. We then set $R(w_1) = 0$, set $R(n) = 0$ for all $n \leq w_1$ on which R is still undefined and terminate the strategy *for now*. However, if at a later time $t > s$, we see that $h(e, t) = 0$ and $A_t \upharpoonright 1 \neq A_{s_1} \upharpoonright 1$, then we resurrect the strategy and start over at the level l where we left off.

We claim that this strategy satisfies the requirement (\mathcal{R}_e) . If Case 1 happens for any witness w_l , the requirement is satisfied. Case 3a can only happen finitely many times at a given level since $A_{s_l} \upharpoonright l$ can only change finitely many times. Case 3b can only happen finitely many times across all levels as each passage through this case causes a flip of $h(e, \cdot)$, and we know $h(e, \cdot)$ converges. Case 2b can also happen only finitely often, because each time we go through this case and do not get to diagonalize, $S(e, \cdot)$ computes a longer initial segment of A , but A is incomputable so $S(e, l)$ would eventually have to be wrong.

Thus we either eventually end up in Case 1 (and immediately succeed) or Case 2a (and immediately succeed) or a terminal Case 3b, i.e., the strategy enters Case 3b and stays there forever. It remains to check this last scenario. Suppose the terminal Case 3b happens for some $A_{s_l} \upharpoonright l$ which is not a prefix of A , this means that $\Psi^A(w_l)$ has not been defined yet and thus, should nothing else happen, we would have $\lim_t h(e, t) = 0$ and would see a change in $A \upharpoonright l$, thus leaving this occurrence of Case 3b, a contradiction. So $A_{s_l} \upharpoonright l$ is indeed a prefix of A and by construction $\Psi^A(w_l)$ returns $0 = R(i)$ in a number of steps t while $\Phi_e(w_l)$ does not return in less than $p_e(t)$ steps, thus the requirement is satisfied. It is now straightforward to satisfy all requirements by ordering them in order of priority, noticing that each strategy only makes finitely many changes to R before achieving its goal and R is total as every time $R(w)$ becomes defined, so do the $R(n)$ for $n \leq w$ that were previously undefined. ◀

It is important to note that Theorem 5 fails to hold outside of the c.e. setting.

► **Theorem 6.** *There exists a low, non-computable set X which is low for speed.*

Proof. See Section 5. ◀

One can also show that Theorem 5 does not extend to other levels of the ‘low’ hierarchy within c.e. sets.

► **Theorem 7.** *There is a low₂ c.e. set that is low for speed.*

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We can also combine the the same ideas (dump construction together with awaiting for certification) with the standard proof that there exists an incomplete c.e. set A of high Turing degree (i.e., $A' \equiv_T \emptyset''$) to get the following.

► **Theorem 8.** *There is a high c.e. set A which is low for speed.*

4 How big is LFS?

Bayer and Slaman showed that whether LFS is meager or not... depends on the answer to P vs NP question! More precisely, if $P = NP$, then LFS is co-meager (even more precisely, every 2-generic is low for speed, see [8, Section 2.24] for a discussion of the various notions of genericity), while if $P \neq NP$, then LFS is meager (more precisely, every recursively generic is not low for speed). They left as an open question whether LFS has measure (Lebesgue) 0 or 1 (by Kolmogorov's 0/1-law, it has to be one or the other). One might expect that, just like the meagerness of LFS depends on the P vs NP question, its measure depends on complexity-theoretic assumptions, such as the 'P vs BPP' question. This is not the case: we show that LFS is – unconditionally – a nullset.

► **Theorem 9.** *The set LFS has measure 0.*

We postpone the proof of this theorem to the next section as it builds upon the proof of Theorem 15.

On the other hand, we will see in the next section that LFS is large in the set-theoretic sense, namely that it has the size of the continuum.

Finally, there is one last notion of size for subsets of $\{0, 1\}^\omega$ that is dear to computability theorists, namely, a set is 'large' if it contains a Turing upper cone and is 'small' if it disjoint from a Turing upper cone. Martin's Turing determinacy theorem tells us that any Borel set which is closed under Turing equivalence must be either large or small on this account. The set LFS is indeed Borel (this is easy to see from the definition), but it is not closed under Turing equivalence, so Martin's theorem does not apply. In the next section, we will use a classical result from complexity theory to show that LFS is in fact disjoint from a Turing upper cone (Theorem 15).

5 Lowness for speed and Turing degrees

While lowness for speed is not closed under Turing equivalence, the following question is nonetheless interesting:

Which sets are Turing equivalent to some low for speed X ? Which sets compute some non-computable low for speed X ?

We denote by **LFS** and **LFS*** the set of Turing degrees that contain a low for speed set and a non-computable low for speed set, respectively. One of the main results of Bayer [4] is that not all degrees are in **LFS**. Indeed, there exists a c.e. degree $\mathbf{a} \notin \mathbf{LFS}$. The main question left open by Bayer regarding **LFS** is whether it is downward closed under \leq_T or closed under join. We give a negative answer to both questions. To show that it is not downward closed, we need the following extension of Theorem 5 to degrees.

► **Theorem 10.** *For any low c.e. degree $\mathbf{a} > \mathbf{0}$, we have $\mathbf{a} \notin \mathbf{LFS}$.*

► **Corollary 11.** *LFS is not downward closed under \leq_T , even within c.e. degrees.*

Proof. Let $\mathbf{a} > \mathbf{0}$ be a c.e. degree in **LFS** whose existence was explained in Section 3. By Sacks's splitting theorem [15], there is a low c.e. degree $\mathbf{0} < \mathbf{b} < \mathbf{a}$. By Theorem 10, $\mathbf{b} \notin \mathbf{LFS}$. ◀

The next theorem will show that while not every c.e. degree contains a low for speed member, every non-zero c.e. degree \mathbf{a} bounds a degree $\mathbf{b} \in \mathbf{LFS}$. Recall Bayer's result that whether 2-generics are low for speed or not depends on the 'P vs NP' question. When it comes to the *degree* of generics, we have that every 1-generic is Turing-equivalent to a set that is low for speed, independently of complexity-theoretic assumptions.

► **Theorem 12.** *Every 1-generic degree \mathbf{g} belongs to \mathbf{LFS}^* .*

Proof. We get this result by refining the proof of Theorem 3. In that proof, we built an X low for speed by finite extension, and ensuring that X was a subset of $S = \{0^{2^n} \mid n \in \mathbb{N}\}$. For $G \subseteq \mathbb{N}$, let $S_G = \{0^{2^n} \mid n \in G\}$. We claim that when G is 1-generic, $S_G = \{0^{2^n} \mid n \in G\}$ is low for speed (and clearly $S_G \equiv_T G$). In the proof of Theorem 3, if we let $\mathcal{U}_{e,i}$ be the effectively open set of those Z such that for some n , $\Phi_e^{S_Z}(n)$ and $R_i(n)$ both converge to different values, we know that G , being 1-generic, is either in $\mathcal{U}_{e,i}$ (hence satisfying the requirement $\mathcal{R}_{e,i}$ as per case (a)), or in the interior of the complement of $\mathcal{U}_{e,i}$, which precisely corresponds to case (b), hence the requirement is also satisfied in this case. ◀

We can derive a number of useful corollaries from this theorem. First of all, we see that **LFS** has the size of the continuum since $G \mapsto S_G$ is one-to-one, and there are continuum many 1-generic G . We also get an immediate proof of Theorem 6 that asserts the existence of a set of low degree that is low for speed.

Proof of Theorem 6. Take a Δ_2^0 1-generic G ; the corresponding set S_G is low for speed and is low because it is both Δ_2^0 and GL_1 (Indeed a result of Jockusch [10] states that every 1-generic degree G is GL_1 , that is, $G' \equiv_T G \oplus \emptyset'$; when $G \leq_T \emptyset'$, this is equivalent to $G' \equiv_T \emptyset'$). ◀

A similar idea allows us to show that **LFS** contains a non-trivial interval in the Turing degrees.

► **Corollary 13.** *There is a degree $\mathbf{a} > \mathbf{0}$ such that every $\mathbf{0} \leq \mathbf{b} \leq \mathbf{a}$ is in **LFS**.*

Proof. By a result of Haught [9], if \mathbf{a} is a Δ_2^0 1-generic degree, every $\mathbf{b} > \mathbf{0}$ below \mathbf{a} is of 1-generic degree. Then the result follows immediately from Theorem 12. ◀

Another interesting corollary is that every non-computable c.e. set bounds a non-computable low for speed set. Likewise almost every set, in the measure-theoretic sense, bounds a non-computable low for speed set.

► **Corollary 14.** *Every non-zero c.e. degree bounds a member \mathbf{LFS}^* , every 2-random degree bounds a member of \mathbf{LFS}^* .*

Proof. This is simply because every non-zero c.e. degree and every 2-random degree bounds a 1-generic degree [13, 11]. ◀

We now show that **LFS** avoids a cone, namely all degrees above $\mathbf{0}'$.

► **Theorem 15.** *If $\mathbf{a} \geq \mathbf{0}'$, then $\mathbf{a} \notin \mathbf{LFS}$.*

Proof. The proof of this theorem relies on the proof of a classical computational complexity theorem, namely Blum’s speed-up theorem [6] (see also [12, Theorem 32.2]), which asserts that for every sufficiently fast growing computable function f , there exists a computable set R which admits no fastest algorithm in that for every i such that $\Phi_i = R$, there is a j such that $\Phi_j = R$ and $f(\text{time}(\Phi_j, x)) \leq \text{time}(\Phi_i, x)$ for almost every x .

Blum’s theorem is proven as follows. We build R by diagonalization against all Φ_i , where for all x in order we try to find an ‘active’ $i \leq |x|$ such that $\Phi_i(x)$ converges in less than $f^{|x|-i}(|x|)$ steps, and if such an i is found, we set $R(x) = 1 - \Phi_i(x)$ for the smallest such i , and declare i inactive from that point on (since we have already ensured $\Phi_i \neq R$, we no longer need to deal with Φ_i). If no such i is found, set $R(x) = 0$. By construction, R is computable, and any Φ_i computing it must satisfy $\text{time}(\Phi_i, x) \geq f^{|x|-i}(|x|)$ for almost all $|x| \geq i$ (otherwise, Φ_i would be diagonalized at some point, because for any x such that $\text{time}(\Phi_i, x) < f^{|x|-i}(|x|)$, the only way Φ_i can escape diagonalization is when some other Φ_j with $j < i$ is diagonalized in priority, but this situation can happen at most i times). Now, suppose Φ_e is a functional that computes R . We need to show that there is another functional which computes R much faster than Φ_e . Fix an integer k and assume we are given as ‘advice’ the finite list σ_k of indices $i < k$ such that Φ_i eventually gets diagonalized against (and therefore i becomes inactive) in the construction of R . Now, we can compute R via the following procedure. In a first phase, simply follow the construction of R as described above, until we reach a point where all $i \in \sigma_k$ have become inactive. At this point, we know (only because we know σ_k !) that none of the $\{\Phi_i \mid i < k\}$ are relevant for the construction of R on future x . Thus, we enter a second phase where to compute each $R(x)$, we only need to simulate, for $k \leq j \leq |x|$, $\Phi_j(x)$ during $f^{|x|-j}(|x|)$ steps of computation. By dovetailing, this can be done in $\text{poly}(|x| \cdot f^{|x|-k}(|x|))$ (the polynomial being independent of k) which, if f is fast growing enough and k large enough compared to e , is $< f^{|x|-e}(|x|)$, which in turn is $< f(\text{time}(\Phi_e, x))$ for almost all x (note that such a k can be computed uniformly given e).

Now, suppose we are given $A \geq_T \emptyset'$. Let $f(n) = 2^n$ and R the corresponding set in Blum’s theorem. Note that in the above, determining whether a given i will eventually become inactive can be done uniformly relative to \emptyset' , and thus the list σ_k can be computed uniformly in k relative to \emptyset' . Thus, using A as oracle, we can consider the procedure Ψ^A which for each pair (Φ_e, p_e) of a functional and a polynomial sequentially, finds the k and σ_k above, checks whether $e \in \sigma_k$, in which case there is nothing to do as $\Phi_e \neq R$ by definition, and if not, use the above 2-phase method to compute R , until a large x is found such that $f(\text{time}(\Psi^A, x)) < \text{time}(\Phi_e, x)$, which for x sufficiently large guarantees $p_e(\text{time}(\Psi^A, x)) < \text{time}(\Phi_e, x)$, and we can then move on to the next index $e + 1$. ◀

► **Theorem 16.** *There are $\mathbf{a}, \mathbf{b} \in \text{LFS}$ such that $\mathbf{a} \vee \mathbf{b} \notin \text{LFS}$*

Proof. Let G_0 be 2-generic, i.e., 1-generic relative to \emptyset' . Consider $G_1 = G_0 \Delta \emptyset'$ where Δ is the symmetric difference. It is easy to check that G_1 is also 2-generic. Thus S_{G_0} and S_{G_1} (defined as in the proof of Theorem 12) are both low for speed (Theorem 12) but $S_{G_0} \oplus S_{G_1} \geq_T G_0 \oplus G_1 \geq_T G_0 \Delta G_1 = \emptyset'$, so by the previous theorem, $\text{deg}(S_{G_0} \oplus S_{G_1}) \notin \text{LFS}$. ◀

Using a diagonalization technique like in Blum’s theorem (though with the same time bound for all functionals), we can prove that LFS has measure 0. In fact, we get a more precise statement in terms of algorithmic randomness.

► **Theorem 17.** *No Schnorr random sequence A is low for speed.*

Proof. The extra ingredient we need on top of Blum's theorem is to make the set R sparse: it will contain at most one string of each length. For each n , we compute $\Phi_i(x)$ during $f(|x|) = 2^{|x|}$ of computation for all x of length n and all active $i \leq n$ (here we don't need to have different time bounds for different functionals; all we need is for f to be computable and sufficiently fast-growing). If for any of these strings we see that $\Phi_i(x)$ converges, we take the smallest such i and then the smallest x for which we see convergence, and set $R(x) = 1 - \Phi_i(x)$, as well as $R(y) = 0$ for all $y \neq x$ of length n , and then declare i inactive. This way we do ensure sparseness of R , and like in the previous proof, that for all i , if Φ_i computes R , $\text{time}(\Phi_i, x) > 2^{|x|}$ for almost all x . On the other hand, consider the following procedure Ψ . Given oracle Z and input x , $\Psi^Z(x)$ first splits Z (viewed as a binary sequence) as $Z = \zeta_1 \zeta_2 \dots$ with $|\zeta_i| = i$ and $\Psi^Z(x)$ returns 0 if $x = \zeta_{|x|}$ (thus the resulting computation is polynomial in $|x|$), and $\Psi^Z(x) = R(x)$ otherwise, using a fixed procedure to compute R . So there is a polynomial p such that for any Z , $\text{time}(\Psi^Z, x) \leq p(|x|)$ for infinitely many x 's. Furthermore, we can only have $\Psi^Z(x) \neq R(x)$ if $x = \zeta_{|x|}$ and $\zeta_{|x|}$ happens to be the only string of its length in R . This has probability at most $2^{-|x|}$ ('at most' because R can also have no string of length $|x|$ at all) if Z is chosen at random. This means that, by setting $C_n = \{Z \mid (\exists x) |x| = n \wedge \Psi^Z(x) \neq R(x)\}$, we have $\lambda(C_n) \leq 2^{-n}$.

The C_n 's are uniformly computable clopen subsets of $\{0, 1\}^\omega$ because Ψ is a truth-table functional. Thus, a Schnorr random A can only belong to finitely many C_n 's (see for example [5, Lemma 1.5.9]), meaning that $\Psi^A(x) = R(x)$ for almost all x . Thus there is a finite variation $\hat{\Psi}$ of Ψ such that $\hat{\Psi}^A = R$, and $\hat{\Psi}^A(x)$ is computed in polynomial time for infinitely many x while $\text{time}(\Phi_i, x) > 2^{|x|}$ for any Φ_i computing R and almost all x . This shows that A is not low for speed. ◀

Theorem 17 shows that **LFS** is a nullset, but it leaves open the possibility that almost all X are *Turing-equivalent* to a low for speed set. This would be similar to the category situation where – under the reasonable assumption $\mathbf{P} \neq \mathbf{NP}$ – the set **LFS** is meager (as proven by Bayer and Slaman) but the set of A 's whose *degree* is in **LFS** is co-meager (Theorem 12). It turns out that **LFS** behaves quite differently in the measure setting:

► **Theorem 18.** *The set $\{A \in \{0, 1\}^\omega \mid \text{deg}(A) \in \mathbf{LFS}\}$ has measure 0.*

At this point, we know that the set of X 's which compute a member of **LFS**^{*} is very large: it has measure 1 and is co-meager, it contains every c.e. set, etc. We might even start thinking that *every* non-computable X computes a member of **LFS**^{*}. This is not the case however, as shown by the following theorem (which contrasts Corollary 13).

► **Theorem 19.** *There is a degree $\mathbf{a} > \mathbf{0}$ such that no $\mathbf{0} < \mathbf{b} \leq \mathbf{a}$ is in **LFS**. Indeed, \mathbf{a} can be chosen to be a minimal Turing degree.*

The classical construction of a minimal degree is done by forcing over total computable function trees (here we follow the terminology of [16]). A function tree is a partial function $T : \{0, 1\}^* \rightarrow \{0, 1\}^*$ such that if either $T(\sigma 0)$ or $T(\sigma 1)$ is defined, then all of $T(\sigma)$, $T(\sigma 0)$ and $T(\sigma 1)$ are, and $T(\sigma 0)$ and $T(\sigma 1)$ are strict extensions of $T(\sigma)$ such that $T(\sigma 0) \perp T(\sigma 1)$ (we say that $T(\sigma 0)$ and $T(\sigma 1)$ split $T(\sigma)$). We say that σ is a node of T if $\sigma \in \text{rng}(T)$. A tree S is a sub-f-tree of T , which we denote by $S \preceq T$ when every node of S is a node of T . An infinite binary sequence Z is a path on an f-tree T if infinitely many prefixes of Z are nodes of T . The set of paths of T is denoted by $[T]$. An f-tree naturally extends to a functional from $\{0, 1\}^\omega$ to $\{0, 1\}^* \cup \{0, 1\}^\omega$ by setting $T(X) = \bigcup_{\sigma \preceq X} T(\sigma)$. When an f-tree T is total, this extension is an homeomorphism from $\{0, 1\}^\omega$ to $\{0, 1\}^\omega$, and if T is furthermore computable, its inverse T^{-1} is also computable. Given a functional Φ_e , we say

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that T is e -consistent if for any two nodes σ and τ on T and any n , if $\Phi_e^\sigma(n)$ and $\Phi_e^\tau(n)$ are both defined, then they are equal; in this case, for any path X of T , Φ_e^X is either partial or computable. We say that T is e -splitting if T is total and for any σ , $\Phi_e^{T(\sigma^0)}$ and $\Phi_e^{T(\sigma^1)}$ are incomparable; in this case, the restriction of Φ_e to $[T]$ is total, one-to-one, and its inverse is computable.

The key lemma in the construction of a minimal degree states that for any total computable f-tree T and every e , there is a total computable sub-f-tree S of T which is either e -consistent or e -splitting. Then an $X \in \{0, 1\}^\omega$ of minimal degree is obtained by taking a sufficiently generic filter G over the set of total computable f-trees ordered by \preceq , and take the intersection of their sets of paths (the non-computability of X can be further ensured by remarking that for any σ , the set of computable f-trees whose nodes are all incomparable with σ is a dense set for the order \preceq , thus one can choose X to avoid any fixed subset of $\{0, 1\}^\omega$, such as its computable elements).

We are going to prove Theorem 19 by showing that taking a sufficiently generic filter for the order \preceq ensures lowness for speed as well. For this, we will make use of the following lemma.

► **Lemma 20.** *Let T be a total computable f-tree. There exists a total computable f-subtree $S \preceq T$ none of whose paths is low for speed.*

Proof. The functional $T^{-1} : [T] \rightarrow \{0, 1\}^\omega$ is total on its domain, which is a Π_1^0 class, and thus is a tt-reduction by effective compactness. Let f be a computable time bound for the running time of T^{-1} , that is, for any $Y \in [T]$, whether $x \in T^{-1}(Y)$ can be decided in time $f(|x|)$ with access to oracle Y . Now, let L be a computable set that cannot be computed in time $2^{f(n+1)}$. Let S be the sub-f-tree of T defined by $S(\sigma) = T(\sigma \oplus L)$ (where $\sigma \oplus L = \sigma(0)L(0) \dots \sigma(k-1)L(k-1)$ when $k = |\sigma|$). The paths of S are exactly the sets of the form $T(X \oplus L)$ for some X . Each of them computes L in time $f(n+1)$ by definition of f , which is exponentially faster than any procedure computing L without oracle by our assumption on L . ◀

Proof of Theorem 19. Let T be a total computable f-tree and Φ_e a functional. As we explained earlier, the usual construction of a minimal degree shows that there is $S \preceq T$ which is either e -consistent or e -splitting. In the case S is e -consistent, we are satisfied (this guarantees Φ_e^A to be either partial or computable). If it is e -splitting, we further refine S as follows. Since S is e -splitting, we consider the total computable f-tree S' corresponding to the image of S by Φ_e : $S'(\sigma) = \Phi_e^{S(\sigma)}$ (this is indeed an f-tree precisely because S is e -splitting). By the previous lemma, there is a total computable $S'' \preceq S'$ none of whose paths is low for speed. Now the pullback $T' = \Phi_e^{-1}(S'')$ is a total computable f-subtree of T , which forces Φ_e^A to not be low for speed.

Thus we can force for all e that Φ_e^A is partial or not low for speed, and force A to be of minimal degree and be non-computable as usual. ◀

Our last theorem shows that the analogue of the low basis theorem (which asserts that every non-empty Π_1^0 class contains a member of low Turing degree) for lowness for speed fails.

► **Theorem 21.** *If \mathbf{a} is a PA-degree, $\mathbf{a} \notin \mathbf{LFS}$. Thus there is a non-empty Π_1^0 class such that no member has a low for speed degree.*

Note that this is in fact a stronger statement than Theorem 15 since $\mathbf{0}'$ is a PA-degree.

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