

Exponential-Size Circuit Complexity is Comeager in Symmetric Exponential Time

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Abstract

Lutz (1987) introduced resource-bounded category and showed the circuit size class $\text{SIZE}(\frac{2^n}{n})$ is meager within SPACE . Li (2024) established that the symmetric alternation class S_2^E contains problems requiring circuits of size $\frac{2^n}{n}$.

In this note, we extend resource-bounded category to S_2^E by defining meagerness relative to single-valued FS_2^P strategies in the Banach-Mazur game. We show that Li's FS_2^P algorithm for the Range Avoidance problem yields a winning strategy, proving that $\text{SIZE}(\frac{2^n}{n})$ is meager in S_2^E .

Consequently, languages requiring exponential-size circuits are comeager in S_2^E : they are typical with respect to resource-bounded category.

1 Introduction

Resource-bounded category, introduced by Lutz [14–16], provides a way to analyze the typical properties of complexity classes using topological notions of size. Lutz showed that the class $\text{SIZE}(\frac{2^n}{n})$ of languages decidable by circuits of size $\frac{2^n}{n}$ is *meager* within the exponential-space class SPACE .

Theorem 1.1. (Lutz [14–16]) $\text{SIZE}(\frac{2^n}{n})$ is meager in SPACE .

The symmetric exponential-time class S_2^E is an exponential version of the class S_2^P [5, 21] and it lies between E and SPACE . Building on work by Korten [12] and Chen, Hirahara, and Ren [6], Li [13] recently proved that S_2^E contains languages that require near-maximum circuit size.

Theorem 1.2. (Li [13]) $S_2^E \not\subseteq \text{SIZE}(\frac{2^n}{n})$.

This solved a longstanding open problem to show the second level of the exponential-time hierarchy requires exponential-size circuits [1–3, 9, 10, 19, 20]. Li's proof technique involves constructing a hard language using a *single-valued* FS_2^P algorithm (a function problem analogue of S_2^P). Given these developments, a natural question is whether the category framework can be refined to operate within S_2^E . Can we show that languages requiring large circuits are not just present, but are in fact *typical* within S_2^E ?

In this note, we answer this question affirmatively. We adapt the resource-bounded category machinery to the class S_2^E by defining meagerness relative to single-valued FS_2^P -computable constructors in the Banach-Mazur game. Our main result shows that, analogous to Lutz's result for SPACE , small circuits are atypical within S_2^E .

Theorem 1.3. $\text{SIZE}(\frac{2^n}{n})$ is meager in S_2^E .

We prove this by demonstrating that Li's single-valued FS_2^P algorithm for the range avoidance problem [6, 12] provides a winning strategy against $\text{SIZE}(\frac{2^n}{n})$ in the appropriate Banach-Mazur game. Thus, languages requiring exponential-size circuits are not just present in S_2^E —they are typical in the sense of resource-bounded category: the class of such languages is comeager in S_2^E .

This paper is organized as follows. We present preliminaries on resource-bounded category and symmetric alternation in Section 2. Our results are in Section 3. We conclude in Section 4 with an open question about extending our results to resource-bounded measure.

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2 Preliminaries

2.1 Resource-Bounded Category

Resource-bounded category was introduced by Lutz [14–16]. The *Cantor space* C is the set of all infinite binary sequences. A *language* (or *decision problem*) is a subset of $\{0, 1\}^*$. We identify each language with the element of Cantor space that is its characteristic sequence according to the standard enumeration $s_0 = \lambda, s_1 = 0, s_2 = 1, s_3 = 00, \dots$ of $\{0, 1\}^*$. In this way, complexity classes (sets of languages) are viewed as subsets of Cantor space.

Baire category classifies sets into two types: *first category* and *second category*. First category sets are also commonly called *meager*. A set is meager if it is a countable union of nowhere dense sets. An equivalent definition comes from Banach-Mazur games using functions called constructors.

Definition 2.1. A *constructor* is a total, single-valued function $\delta : \{0, 1\}^* \rightarrow \{0, 1\}^*$ which satisfies $x \sqsubset_{\neq} \delta(x)$ for all $x \in \{0, 1\}^*$. The *result* of a constructor is the unique sequence $R(\delta) \in C$ that extends $\delta^{(n)}(\lambda)$ for all n .

Let $X \subseteq C$ and let Γ_I and Γ_{II} be two classes of functions. In the *Banach-Mazur game* $G[X; \Gamma_I, \Gamma_{II}]$ there are two players I and II. A *strategy* in the game is a constructor. In a play of the game, player I chooses a strategy $\gamma \in \Gamma_I$ and player II chooses a strategy $\delta \in \Gamma_{II}$. The *result* of this play is the sequence $R(\gamma, \delta) = R(\delta \circ \gamma)$. Intuitively, the result is the sequence obtained when the two players start with the empty string and take turns extending it with their strategies. A *winning strategy* for player II is a strategy $\delta \in \Gamma_{II}$ such that for every $\gamma \in \Gamma_I$, $R(\gamma, \delta) \notin X$.

Theorem 2.2. (Banach and Mazur) *A class $X \subseteq C$ is meager if and only if player II has a winning strategy in the game $G[X; \text{all}, \text{all}]$.*

In resource-bounded category, Δ denotes a *resource bound* [16, 17]. Examples of Δ include:

$$\begin{aligned} \text{all} &= \{f \mid f : \{0, 1\}^* \rightarrow \{0, 1\}^*\} \\ \text{p} &= \{f \mid f \text{ is polynomial-time computable}\} \\ \text{pspace} &= \{f \mid f \text{ is polynomial-space computable}\} \end{aligned}$$

For a resource bound Δ , we define the *result class*

$$R(\Delta) = \{R(\delta) \mid \delta \in \Delta \text{ is a constructor}\}.$$

Then $R(\text{all}) = C$, $R(\text{p}) = E$, and $R(\text{pspace}) = \text{ESPACE}$ [16]. Resource-bounded category [16] is defined by requiring player II's winning strategy to be computable within a resource bound Δ .

Definition 2.3. Let $X \subseteq C$ and let Δ be a resource bound.

1. X is Δ -*meager* if player II has a winning strategy in the game $G[X; \text{all}, \Delta]$.
2. X is Δ -*comeager* if X^c is Δ -meager.
3. X is *meager in* $R(\Delta)$ if $X \cap R(\Delta)$ is Δ -meager.
4. X is *comeager in* $R(\Delta)$ if X^c is meager in $R(\Delta)$.

The *resource-bounded Baire category theorem* [16] tells us that $R(\Delta)$ is not Δ -meager.

2.2 Symmetric Alternation

Symmetric alternation is a concept in computational complexity theory introduced independently by Canetti [5] and Russell and Sundaram [21] with different, but equivalent definitions [4]. We follow the definition due to Canetti.

Definition 2.4. Let $T: \mathbb{N} \rightarrow \mathbb{N}$. We say that a language $L \in \text{S}_2\text{TIME}[T(n)]$ if there exists an $O(T(n))$ -time verifier $V(x, \pi_1, \pi_2)$ that takes $x \in \{0, 1\}^n$ and $\pi_1, \pi_2 \in \{0, 1\}^{T(n)}$ as input, satisfying

$$(\exists \pi_1)(\forall \pi_2)V(x, \pi_1, \pi_2) = \chi_L(x)$$

and

$$(\exists \pi_2)(\forall \pi_1)V(x, \pi_1, \pi_2) = \chi_L(x).$$

Definition 2.5. We define the symmetric alternation complexity classes

$$\text{S}_2^{\text{P}} = \bigcup_{c=1}^{\infty} \text{S}_2\text{TIME}[n^c].$$

and

$$\text{S}_2^{\text{E}} = \bigcup_{c=1}^{\infty} \text{S}_2\text{TIME}[2^{cn}].$$

Symmetric alternation is used to compute single-valued functions as follows [13].

Definition 2.6. A single-valued FS_2^{P} algorithm A is specified by a polynomial $\ell(\cdot)$ together with a polynomial-time verifier $V_A(x, \pi_1, \pi_2)$. On input $x \in \{0, 1\}^*$, we say that A outputs a string $y_x \in \{0, 1\}^*$ if the following two conditions hold:

1. There exists $\pi_1 \in \{0, 1\}^{\ell(|x|)}$ such that for every $\pi_2 \in \{0, 1\}^{\ell(|x|)}$,

$$V_A(x, \pi_1, \pi_2) = y_x.$$

2. There exists $\pi_2 \in \{0, 1\}^{\ell(|x|)}$ such that for every $\pi_1 \in \{0, 1\}^{\ell(|x|)}$,

$$V_A(x, \pi_1, \pi_2) = y_x.$$

Note that Definition 2.4 prescribes a single-valued FS_2^{P} algorithm for χ_L .

Li [13] used a single-valued FS_2^{P} algorithm for the range avoidance problem [6, 12] to prove Theorem 1.2 that S_2^{E} requires exponential-size circuits. The following is a corollary to Li's proof.

Theorem 2.7. (Li [13]) *There is an FS_2^{P} algorithm \mathcal{A} that on input 0^{2^n} outputs a truth-table $f \in \{0, 1\}^{2^n}$ such that f has circuit complexity at least $\frac{2^n}{n}$.*

Remark 2.8. The $\frac{2^n}{n}$ bound in Theorem 1.2, Theorem 2.7, and our results in Section 3 may be replaced by $\frac{2^n}{n} \left(1 + \frac{\alpha \log n}{n}\right)$ for any fixed $\alpha \in (0, 1)$ [7, 8, 17]. We use $\frac{2^n}{n}$ to simplify notation.

3 Category in Symmetric Exponential Time

Recall that $R(\text{P}) = \text{E}$ and $R(\text{PSPACE}) = \text{ESPACE}$. We now show that the result class of FS_2^{P} is S_2^{E} .

Lemma 3.1. $R(\text{FS}_2^{\text{P}}) = \text{S}_2^{\text{E}}$.

Proof. Let $L = R(A)$ where A is a single-valued FS_2^{P} algorithm. Let V_A be as in Definition 2.6. On input x , let n be the index such that $s_n = x$. The idea is to start with $z_0 = \lambda$ and compute $z_{i+1} = A(z_i)$ until $|z_i| > n$. Then the answer for x is $z_i[n]$. We make at most $n \leq 2^{|x|}$ calls to A . Formally, define a verifier V that on input $s_n = x$ also takes two tuples of proofs $t_1 = \langle \pi_1^{(0)}, \dots, \pi_1^{(k-1)} \rangle$ and $t_2 = \langle \pi_2^{(0)}, \dots, \pi_2^{(k-1)} \rangle$. Then we compute $z_0 = \lambda$ and $z_{i+1} = V_A(z_i, \pi_1^{(i)}, \pi_2^{(i)})$ for each $0 \leq i < k$. If $z_i \sqsubset_{\neq} z_{i+1}$ for all i and $|z_k| > n$, then $V(x, t_1, t_2)$ outputs

$z_i[n]$. Otherwise, $V(x, t_1, t_2)$ outputs 0. The total length of the proofs is polynomial in n , so the total proof length is $2^{O(|x|)}$. Since V_A is polynomial-time, V runs in exponential-time and it follows that $L \in S_2^E$.

Let $L \in S_2^E$ and let V be a verifier for L as in Definition 2.4. On input z , we let $n = |z|$. We use V on input s_n to extend z by one bit. If $V(s_n, \pi_1, \pi_2) = 1$, we output $V'(z, \pi_1, \pi_2) = z1$. If $V(s_n, \pi_1, \pi_2) = 0$, we output $V'(z, \pi_1, \pi_2) = z0$. Then V' specifies a single-valued FS_2^P algorithm because $|s_n|$ is logarithmic in $|z|$. We have $R(V') = L$, so $L \in R(FS_2^P)$. \square

We can now fully specify the symmetric alternation category notion used in this paper. We plug Lemma 3.1 into Definition 2.3:

1. X is FS_2^P -meager if player II has a winning strategy in the game $G[X; \text{all}, FS_2^P]$.
2. X is FS_2^P -comeager if X^c is FS_2^P -meager.
3. X is meager in S_2^E if $X \cap S_2^E$ is FS_2^P -meager.
4. X is comeager in S_2^E if X^c is meager in S_2^E .

Lutz [14] proved that $SIZE(\frac{2^n}{n})$ is meager in $ESPACE$ where the strategy uses a brute force voting method inspired by Kannan [10]. We can replace this by Li's single-valued FS_2^P algorithm from Theorem 2.7.

Theorem 3.2. $SIZE(\frac{2^n}{n})$ is FS_2^P -meager.

Proof. Let \mathcal{A} be the algorithm from Theorem 2.7. On input x , compute n so that $2^{n-1} \leq |x| \leq 2^n - 1$. Let $s(n) = \frac{2^n}{n}$. Our constructor δ outputs

$$\delta(x) = x0^{2^n - |x| - 1}\mathcal{A}(0^{2^n}).$$

The $0^{2^n - |x| - 1}$ is to finish defining the language at length $n - 1$. We then use \mathcal{A} to define the language at length n . Thus $|\delta(x)| = 2^{n+1} - 1$ and $\delta(x)$ defines a subset of $\{0, 1\}^{\leq n}$.

Let γ be any constructor. Then for infinitely many lengths n , $R(\gamma, \delta) = R(\delta \circ \gamma)$ does not have an $s(n)$ -size circuit at length n . Therefore $R(\gamma, \delta) \notin SIZE(s(n))$ and δ wins the Banach-Mazur game, so $SIZE(s(n))$ is FS_2^P -meager. \square

Theorem 1.3 is a corollary of Theorem 3.2, because FS_2^P -meager implies meager in S_2^E .

Theorem 1.3. $SIZE(\frac{2^n}{n})$ is meager in S_2^E .

Our title result follows immediately from Theorem 1.3.

Corollary 3.3. *The class of problems requiring exponential-size circuits is comeager in S_2^E .*

Another corollary is meagerness of $SIZE(\frac{2^n}{n})$ in E^{NP} under a derandomization hypothesis. This is because standard derandomization hypotheses [11] collapse FS_2^P to FP^{NP} via derandomization of $FZPP^{NP}$. Resource-bounded category in E^{NP} is defined analogously to category in E , using polynomial-time constructors that have access to an NP oracle in Definition 2.3.

Lemma 3.4. $R(FP^{NP}) = E^{NP}$.

1. X is FP^{NP} -meager if player II has a winning strategy in the game $G[X; \text{all}, FP^{NP}]$.
2. X is meager in E^{NP} if $X \cap E^{NP}$ is FP^{NP} -meager.

Corollary 3.5. *If E^{NP} requires $2^{\Omega(n)}$ -size NP-oracle circuits, then $SIZE(\frac{2^n}{n})$ is meager in E^{NP} .*

Proof. Cai [4] showed that $S_2^P \subseteq ZPP^{NP}$. It also holds that single-valued FS_2^P is contained in single-valued $FZPP^{NP}$ [6]. Under the hypothesis, techniques of Klivans and van Melkebeek [11] derandomize $FZPP^{NP}$ to FP^{NP} [6]. Thus the constructor in the proof of Theorem 3.2 is in FP^{NP} , so $SIZE(\frac{2^n}{n})$ is FP^{NP} -meager and is meager in E^{NP} . \square

4 Conclusion

Lutz and Mayordomo [18] asked if P/poly has measure 0 in a class smaller than Δ_3^E , the third level of the exponential-time hierarchy. Theorem 1.3 implies P/poly is meager in S_2^E . Resource-bounded measure may also be defined in S_2^E using single-valued FS_2^P martingales. Does P/poly have measure 0 in S_2^E ?

Acknowledgement. I thank an anonymous referee for helpful comments.

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