

# Total Search Problems in ZPP

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## Abstract

We initiate a systematic study of **TFZPP**, the class of total NP search problems solvable by polynomial time randomized algorithms. **TFZPP** contains a variety of important search problems such as **BERTRAND-CHEBYSHEV** (finding a prime between  $N$  and  $2N$ ), refuter problems for many circuit lower bounds, and **LOSSY-CODE**. The **LOSSY-CODE** problem has found prominence due to its fundamental connections to derandomization, catalytic computing, and the metamathematics of complexity theory, among other areas.

While **TFZPP** collapses to **FP** under standard derandomization assumptions in the white-box setting, we are able to separate **TFZPP** from the major **TFNP** subclasses in the black-box setting. In fact, we are able to separate it from every uniform **TFNP** class assuming that **NP** is not in quasi-polynomial time. To do so, we extend the connection between proof complexity and black-box **TFNP** to randomized proof systems and randomized reductions.

Next, we turn to developing a taxonomy of **TFZPP** problems. We highlight a problem called **NEPHEW**, originating from an infinity axiom in set theory. We show that **NEPHEW** is in **PWPP**  $\cap$  **TFZPP** and conjecture that it is not reducible to **LOSSY-CODE**. Intriguingly, except for some artificial examples, most other black-box **TFZPP** problems that we are aware of reduce to **LOSSY-CODE**:

- We define a problem called **EMPTY-CHILD** capturing finding a leaf in a rooted (binary) tree, and show that this problem is *equivalent* to **LOSSY-CODE**. We also show that a variant of **EMPTY-CHILD** with “heights” is complete for the intersection of **SOPL** and **LOSSY-CODE**.
- We strengthen **LOSSY-CODE** with several combinatorial inequalities such as the AM-GM inequality. Somewhat surprisingly, we show the resulting new problems are still reducible to **LOSSY-CODE**. A technical highlight of this result is that they are proved by *formalizations in bounded arithmetic*, specifically in Jeřábek’s theory **APC**<sub>1</sub> (JSL 2007).
- Finally, we show that the **DENSE-LINEAR-ORDERING** problem reduces to **LOSSY-CODE**.

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# 1 Introduction

Total search problems are abundant in theoretical computer science. The formal study of these problems has been highly impactful to a wide range of areas including game theory [DGP09, CD06], cryptography [HKKS20, FGH<sup>+</sup>24, BGSD25], proof complexity [BCE<sup>+</sup>98, DR23, LPR24, GHJ<sup>+</sup>22, Tha24, GKRS19, LLR24, FIM25], and recently in the study of explicit construction problems and derandomization [KKMP21, Kor21, Kor25]. Central to the latter has been the *Range Avoidance* (or simply **AVOID**) problem.

**AVOID.** Given a circuit  $D : \{0, 1\}^{n-1} \rightarrow \{0, 1\}^n$ , find  $x \in \{0, 1\}^n$  such that for every  $y \in \{0, 1\}^{n-1}$ ,  $D(y) \neq x$ .

**AVOID** captures the explicit construction problems for many combinatorial objects whose existence follows from the probabilistic method. Notable examples include functions with high circuit complexity, rigid matrices, Ramsey graphs, strong error correcting codes, and many more [Kor21, Jeř07a, GLW25, GGNS23]. By developing algorithms for **AVOID**, a line of work has shown circuit lower bounds against a variety of classes [RSW22, CHLR23, CHR24, Li24].

**AVOID** belongs to the class  $\text{TF}\Sigma_2^P$ , the second level of the total function polynomial hierarchy. If one *Herbrandizes*<sup>1</sup> the **AVOID** problem, then one obtains its **TFNP** sibling, the **LOSSY-CODE** problem (see [Kor25] for a survey). This problem asks to find an element that is not in the range of a pair of compressing and decompressing maps  $C$  and  $D$ .

**LOSSY-CODE.** Given a pair of circuits  $C : \{0, 1\}^n \rightarrow \{0, 1\}^{n-1}$  and  $D : \{0, 1\}^{n-1} \rightarrow \{0, 1\}^n$ , find  $x \in \{0, 1\}^n$  such that  $D(C(x)) \neq x$ .

**LOSSY-CODE** was originally defined by Jeřábek in [Jeř07a, Jeř07b], under the name *retraction weak pigeonhole principle*, showing that it is equivalent to the set of problems whose totality is provable in  $\text{APC}_1$ . Since then, it has been considered predominantly through the lens of bounded arithmetic as a **TFNP** problem and as a combinatorial principle [Mül21, KT22]. Korten [Kor22] asked to understand the set of **TFNP** problems that are reducible to **LOSSY-CODE**. Besides being an interesting problem on its own, **LOSSY-CODE** also arises naturally in a few other places, further motivating its study:

- **Derandomization.** In the recent *certified derandomization* framework [PRZ23], the derandomization algorithm is required to either output the correct answer, or report that the underlying circuit lower bound assumption is false by providing a small circuit violating the assumption. It turns out that certified derandomization is characterized by **LOSSY-CODE** [LPT24].

Such derandomization ideas are particularly explored in the context of *catalytic computing* [BCK<sup>+</sup>14, Mer23] in a framework known as “compress-or-random” [Pyn24, CLMP25, KMP25, AM25]: If the contents of the catalytic tape is “incompressible” (which usually means that it is not a solution of a certain **LOSSY-CODE** instance), then it can be used for derandomization; otherwise we can compress the catalytic tape and obtain more free space. As a result, although we are currently unable to prove that **CL** (catalytic logspace) is in **P**, we can show that **CL** reduces to **LOSSY-CODE** [CLMP25].

- **Metamathematics of complexity theory.** It turns out that (variants of) **LOSSY-CODE** captures the complexity of many *refuter* problems [CJSW24], which are natural total search problems reflecting the metamathematical complexity of proving lower bounds. Many lower bounds in circuit complexity and communication complexity have refuter problems equivalent to **LOSSY-CODE** [Kor22, CLO24], and the refuter complexity for some proof complexity lower bounds is captured by variants of **LOSSY-CODE** as well [LLR24].

<sup>1</sup>Herbrandization is a basic construction in logic; see [Appendix A](#) for a short overview.

- **Bounded arithmetic.** A basic theory of bounded arithmetic for approximate counting and reasoning about randomized computation is  $\text{APC}_1$ , developed in a series of papers by Jeřábek [Jeř04, Jeř05, Jeř07a]. Wilkie’s witnessing theorem [Tha02, Jeř04] implies that  $\text{LOSSY-CODE}$  is “complete” for  $\text{APC}_1$  in the following sense:  $\text{APC}_1$  proves the totality of  $\text{LOSSY-CODE}$ , and every  $\text{TFNP}$  problem provably total in  $\text{APC}_1$  reduces to  $\text{LOSSY-CODE}$ .

$\text{LOSSY-CODE}$  belongs to the class  $\text{TFZPP}$ , the subclass of  $\text{TFNP}$  containing the total search problems that admit polynomial-time randomized algorithms, introduced in [BO06]. Since we are dealing with total  $\text{NP}$  search problems, every randomized algorithm that may make mistakes can be turned into one that does not make any mistakes.<sup>2</sup> Hence, it seems that  $\text{TFZPP}$  is the only natural (semantic) subclass of  $\text{TFNP}$  capturing randomized polynomial time.

Besides  $\text{LOSSY-CODE}$ , there are a variety of important total search problems that sit inside  $\text{TFZPP}$ . We list two of them that we think reflect the importance of  $\text{TFZPP}$  the best:

**Example 1.1.** The Bertrand–Chebyshev theorem states that for every integer  $N \geq 1$ , there is a prime number between  $N$  and  $2N$ . This motivates the following total search problem called  $\text{BERTRAND-CHEBYSHEV}$ : Given an integer  $N$  (represented in binary), output a prime number between  $N$  and  $2N$ . In fact, the Prime Number Theorem implies that there are  $\Theta(N/\log N)$  such prime numbers, and the AKS primality test [AKS04] provides a deterministic method for verifying solutions, hence  $\text{BERTRAND-CHEBYSHEV}$  is in  $\text{TFZPP}$ .

The complexity of  $\text{BERTRAND-CHEBYSHEV}$  remains elusive. Unless one makes strong assumptions such as Cramér’s conjecture [Cra36] or  $\text{P} = \text{BPP}$  [IW97], the best known deterministic algorithm needs to spend  $\approx N^{1/2}$  time [LO87, BHP01] (which is *exponential* in the input length). Improving this time bound was exactly the focus of the Polymath 4 project [TCH12]; however, despite much effort, no unconditional progress was made. This problem is also the flagship problem in the study of *pseudodeterministic algorithms* [GG11, OS17, LOS21, CLO<sup>+</sup>23].

On the complexity-theoretic side, the only upper bound known for  $\text{BERTRAND-CHEBYSHEV}$  is that it reduces to  $\text{LOSSY-CODE}^{\text{FACTORING}}$ , i.e., the  $\text{LOSSY-CODE}$  problem where both input circuits  $C, D$  have access to a  $\text{FACTORING}$  oracle [PWW88, Kor22]. It is unclear if it belongs to any standard  $\text{TFNP}$  subclasses such as  $\text{PLS}$  or  $\text{PPA}$  [GP18, GL25].

**Example 1.2.** A family of important total search problems is *refuter problems* [CLW20, CJSW24, CTW23] for complexity lower bounds. Let  $\mathcal{C}$  be a circuit class and  $L$  be a hard problem for  $\mathcal{C}$ , the refuter problem,  $\text{REFUTER}(L \notin \mathcal{C})$ , is the following total search problem: given a small  $\mathcal{C}$  circuit  $C$  attempting to compute  $L$ , the goal is to output an instance  $x$  such that  $C(x) \neq L(x)$ . The complexity of these refuter problems are closely related to the provability of complexity lower bounds [CLO24, LLR24].

Such refuter problems are often in  $\text{TFZPP}$ : In fact, if  $L$  is *average-case hard* against  $\mathcal{C}$  (and both  $\mathcal{C}$  and  $L$  are in polynomial-time), then  $\text{REFUTER}(L \notin \mathcal{C}) \in \text{TFZPP}$  as the algorithm for the refuter problem can repeatedly sample inputs from the hard distribution until it finds a solution  $x$  where  $C(x) \neq L(x)$ . Even though average-case lower bounds against  $\text{AC}^0[p]$  circuits have been proved for nearly 40 years [Raz87, Smo87], we are not aware of any non-trivial  $\text{TFNP}$  upper bound for the problem  $\text{REFUTER}(\text{MAJ} \notin \text{AC}^0[2])$ .

Another example is when  $L = \text{search-SAT}$  and  $\mathcal{C}$  is the family of polynomial-size circuits: Given a circuit  $C$  attempting to solve search-SAT, the refuter problem asks to find a formula  $\varphi$  (along with a satisfying assignment  $a$  of  $\varphi$ ) such that  $C(\varphi)$  fails to satisfy  $\varphi$ . The complexity of this problem is of significant interest to the bounded arithmetic community [Kra95, Bus97, Pic15, PS23] as its hardness would imply the unprovability of  $\text{NP} \not\subseteq \text{P/poly}$ . However, this problem is in  $\text{TFZPP}$  under the existence of one-way functions against non-uniform adversaries, hence it is unclear how its complexity sheds light on the aforementioned unprovability question.

Finally, an additional motivation for studying  $\text{TFZPP}$  is its connection to  $\text{AVOID}$  and  $\text{APEPP}$  (the class of total search problems mapping reducible to  $\text{AVOID}$  [KKMP21]): it is the “projection” of  $\text{AVOID}$  to  $\text{TFNP}$  in the following sense:

**Theorem 1.3.**  $\text{TFZPP} = \text{TFNP} \cap \text{APEPP}$ .

<sup>2</sup>This was observed by Jeřábek [Jeř16]; in his terminology, we have  $\text{TFRP} = \text{TFZPP}$ .

## Our Contributions.

In this work, we initiate a formal study of  $\text{TFZPP}$  as a class of total search problems. Analogous to the setting of decision problems, we expect that  $\text{TFZPP} = \text{FP}$ . Indeed, this follows from the same assumption used in [IW97]—namely that  $\text{E}$  requires circuits of exponential size. Moreover,  $\text{TFZPP} = \text{FP}$  appears to be weaker than a full derandomization of  $\text{BPP}$ .

However, we show that this is not the case in the *black-box* setting in a very strong sense. In the black-box setting one only has access to the input via an oracle; black-box classes are denoted by a  $dt$  superscript (for “*decision trees*”). We say that a  $\text{TFNP}^{dt}$  class is *uniformly generated* if it has a complete problem  $R = \{R_n\}_{n \in \mathbb{N}}$  such that there is a Turing Machine which on input  $1^n$  outputs  $R_n$  in polynomial time. Note that all of the major  $\text{TFNP}^{dt}$  subclasses in the literature are uniformly generated. Under the assumption that  $\text{NP}$  is not in quasi-polynomial time (QP), we show that no uniformly generated  $\text{TFNP}^{dt}$  class contains  $\text{TFZPP}^{dt}$ .

**Theorem 1.4.**  $\text{TFZPP}^{dt} \not\subseteq \mathcal{C}$  for every uniformly generated class  $\mathcal{C} \subseteq \text{TFNP}^{dt}$ , unless  $\text{NP} \subseteq \text{QP}$ .

To prove these separations, we employ a close connection between total search problems and proof complexity [BCE<sup>+</sup>98, GKRS19, BFI23, FIM25]. This connection shows that, in the black-box setting, a search problem belongs to a class if and only if an associated proof system can prove the totality of that search problem. In this case, we say that the class is *characterized* by that proof system. To prove our separations, we first show that  $\text{TFZPP}^{dt}$  is characterized by the random tree-like resolution proof systems of Buss et al. [BKT14].

**Theorem 1.5.**  $\text{TFZPP}^{dt}$  is characterized by random tree-like resolution.

More generally, we show that if a class  $\mathcal{C}$  of total search problems is characterized by a proof system  $\Pi$ , then the class of problems that are efficiently *randomized* reducible to a complete problem in  $\mathcal{C}$  is characterized by the proof system random  $\Pi$ . [Theorem 1.4](#) then follows by combining the following two results: (1) Buss et al. [BFI23] showed that every uniformly generated  $\text{TFNP}$  class has a characterizing proof system, and (2) Pudlák and Thapen [PT19] showed that a propositional proof system simulating random tree-like resolution would imply faster algorithms for  $\text{NP}$ .

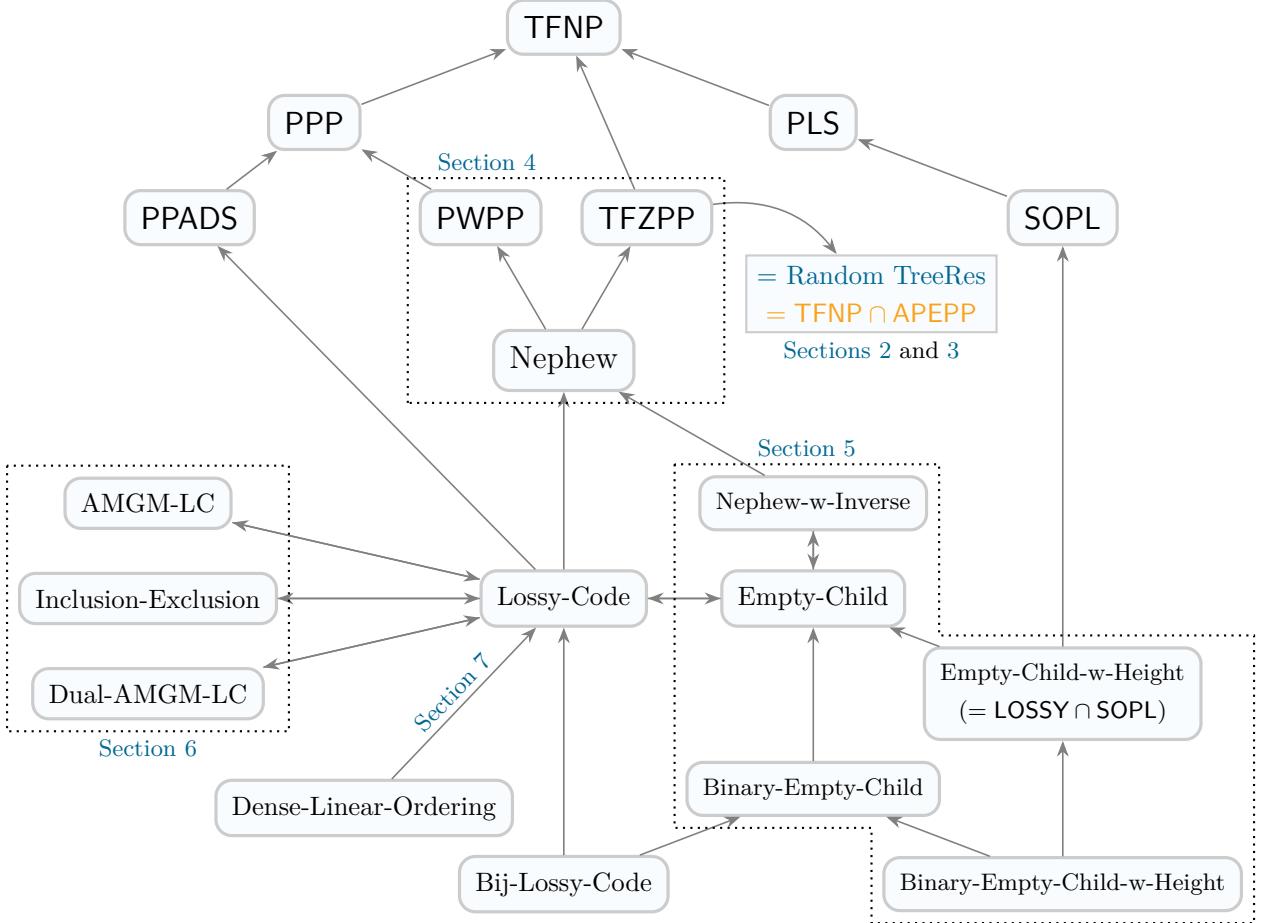
**A Highly Unsatisfiable Cook-Reckhow Program.** [Theorem 1.4](#) is striking as it suggests that  $\text{TFZPP}$  problems can be arbitrarily hard in the black-box model. This motivates an interesting direction of research: find explicit  $\text{TFZPP}$  problems that are hard for stronger and stronger subclasses of  $\text{TFNP}^{dt}$ . By the close connection between  $\text{TFNP}^{dt}$  and proof complexity [BFI23], this can be seen as a Cook-Reckhow program for highly unsatisfiable formulas: for increasingly more expressive proof systems, exhibit a highly unsatisfiable CNF formula which is hard for that system.

Towards this program, we provide explicit separations of  $\text{TFZPP}^{dt}$  from every major  $\text{TFNP}$  class defined in the 1990s [JPY88, Pap94]. Note that all those  $\text{TFNP}$  classes are contained in  $\text{PLS}$ ,  $\text{PPP}$ , and  $\text{PPA}$ . The separation from  $\text{PPA}$  was shown by Beame et al. [BCE<sup>+</sup>98]. Leveraging the recent work of Hopkins and Lin [HL22], we are able to show the following.

**Theorem 1.6.** There are *explicit* (polynomial-time constructable) problems in  $\text{TFZPP}^{dt}$  which are not in either  $\text{PPP}^{dt}$  or  $\text{PLS}^{dt}$ .

## A $\text{TFZPP}$ Zoo.

We now turn to studying the structure of problems inside of  $\text{TFZPP}$ . [Figure 1](#) shows the zoo of problems within  $\text{TFZPP}$  that we consider, as well as their relationships.



**Figure 1:** The TFZPP zoo.

Like ZPP, TFZPP is a semantic class and therefore it is unlikely to admit complete problems unless  $\text{FP} = \text{TFZPP}$ . However, we observe an interesting phenomenon: almost every TFZPP problem that has been studied in the literature is reducible to Lossy-Code!<sup>3</sup> This raises the question: are there “natural” TFZPP problems which are not reducible Lossy-Code in the black-box setting, and what do they look like? [Theorem 1.4](#) and [Theorem 1.6](#) already provide examples of problems that are not reducible to Lossy-Code; however, we do not consider these problems natural—we are looking for problems that would be studied outside of the context of proving such separations.

While we are unable to resolve this question—indeed, many of our conjectured separating examples turned out to be reducible to Lossy-Code in surprising ways!—we provide natural TFZPP problems which we conjecture witness a separation, and which we believe are of independent interest. As well, we show several surprising reductions to Lossy-Code.

**Nephew.** Our primary candidate is the following.

<sup>3</sup>One exception is the Bertrand–Chebyshev problem for which it is not known whether it is reducible to Lossy-Code. However, it is unclear how to define the Bertrand–Chebyshev problem in the *black-box* model, and we are unable to separate any natural black-box TFZPP problem from Lossy-Code.

**NEPHEW.** Given a set  $V$  of vertices and two functions  $f : V \rightarrow V$  and  $g : V \rightarrow V$ . Think of  $f(v)$  as the *father* of  $v$  and  $g(v)$  as the *nephew* of  $v$ . A solution is one of the following.

- s1.**  $v \in V$  such that  $f(f(g(v))) \neq f(v)$  (your nephew's grandparent is not your parent)
- s2.**  $v \in V$  such that  $f(g(v)) = v$  (you are your nephew's parent)

It may not be immediately obvious that NEPHEW is a total search problem. A proof may be found in the textbook of Börger, Grädel, and Gurevich [BGG01, Proposition 6.5.5]; we sketch the argument here. Create a directed graph  $G_f$  with vertex set  $V$  and with an edge from  $u$  to  $v$  if  $f(u) = v$ . Then one can assign to each vertex a “level” that represents its distance to the core<sup>4</sup> of  $G_f$ . Let  $v^*$  be a vertex with maximum level  $\ell_{\max}$ . However, if  $v^*$  is not a solution to NEPHEW, it must be that  $g(v^*)$  has level  $\ell_{\max} + 1$ , a contradiction. A similar intuition will be used in [Section 4](#) for other proofs involving NEPHEW.

NEPHEW is derived from the minimal *axioms of infinity* in model theory. One method for constructing a total search problem is to begin with a sentence in logic that has an infinite model but no finite model. Such a sentence is known as an *axiom of infinity*, since any model for it must be infinite. Axioms of infinity are classified under the number of quantifiers and predicate and function symbols of certain arity that they contain, and there are 10 minimal classes ([BGG01, Theorem 6.5.4]). Each of these classes corresponds to a total search problem, and in most cases, this problem is complete for a well-known TFNP class. The only exception is the one to which NEPHEW belongs; NEPHEW can be interpreted as the Herbrandization of

$$\forall x \exists y (F(F(y)) = F(x) \wedge F(y) \neq x). \quad (1)$$

The proof that NEPHEW belongs to TFZPP is highly non-trivial. Furthermore, our best upper bound on the complexity of NEPHEW is that it is contained within PWPP, the problems reducible to the weak pigeonhole principle, a relaxation of the LOSSY-CODE problem.

**Theorem 1.7.**  $\text{NEPHEW} \in \text{TFZPP} \cap \text{PWPP}$ .

To obtain evidence that NEPHEW is not reducible LOSSY-CODE, we attempt to isolate the potential hardness in NEPHEW. In doing so, we define a number of natural problems in TFZPP which may be of independent interest.

The proof that NEPHEW is in TFZPP proceeds by reducing it to the observation that a leaf in a binary tree can be found in logarithmic time in expectation. We define a total search problem whose membership in TFZPP formalizes this observation.

**EMPTY-CHILD.** Given a set  $V$  of vertices and three functions  $F, L, R : V \rightarrow V$ , where  $F(u)$  is the father of  $u$ , and  $L(u), R(u)$  are the left and the right child of  $u$  respectively, a solution is one of the following.

- s1.**  $u \in V$  such that  $F(L(u)) \neq u$  or  $F(R(u)) \neq u$  or  $L(u) = R(u) \neq u$ ; (Empty child)
- s2.**  $1$ , if  $L(1) = 1$  or  $R(1) = 1$  or  $F(1) \neq 1$ . (Wrong root)

Surprisingly, EMPTY-CHILD is equivalent to LOSSY-CODE under decision tree reductions, denoted  $=_{dt}$ . Thus, if NEPHEW is indeed not reducible to LOSSY-CODE, the hardness of NEPHEW does not come from this portion of the reduction.

**Theorem 1.8.**  $\text{EMPTY-CHILD} =_{dt} \text{LOSSY-CODE}$ .

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<sup>4</sup>We intentionally leave “core” undefined for this brief sketch.

As a warm-up to the techniques needed to prove this theorem, we consider a variant of **EMPTY-CHILD** which includes an additional “height” function that outputs the height of a given node in the tree. We show that this is a complete problem for the class  $\text{LOSSY} \cap \text{PLS} = \text{LOSSY} \cap \text{SOPL}$ , where **LOSSY** is the class of problems efficiently reducible to **LOSSY-CODE**. The proof resembles previous intersection theorems from **TFNP** [FGHS23, GHJ<sup>+</sup>24].

Then, we use **EMPTY-CHILD** as an intermediate problem to study the relationship between **NEPHEW** and **LOSSY-CODE**.

**Theorem 1.9.**  $\text{EMPTY-CHILD} \leq_{dt} \text{NEPHEW}$ .

Thus, combining with Theorem 1.8, we have **LOSSY-CODE** reduces to **NEPHEW**.

**AM-GM Lossy-Code.** One of our original (and failed) candidates for separation from **LOSSY-CODE** was a problem called *AM-GM Lossy-Code*, obtained by combining **LOSSY-CODE** itself with the *AM-GM Inequality*:  $\frac{a+b}{2} \geq \sqrt{ab}$ . This problem was inspired by the **BAD 2-COLORING** problem in [PPY23]: Given an undirected graph  $G = (V, E)$  with  $|V| = 2N$  vertices and  $|E| = N^2 + 1$  edges along with a 2-coloring  $C : V \rightarrow \{0, 1\}$  of  $V$ , find an edge  $(x, y) \in E$  that is not colored properly. This problem is total exactly because of the AM-GM inequality: suppose there are  $a$  black vertices and  $b = 2N - a$  white vertices and every edge is colored properly, then there are at most  $ab \leq \left(\frac{a+b}{2}\right)^2 = N^2$  edges, contradicting  $|E| > N^2$ .

To compose this problem with **LOSSY-CODE**, we need to make two adaptations: First, to put it inside **TFZPP**, the number of edges needs to be *much* larger than  $N^2$ , say  $(1 + \varepsilon)N^2$ ; second, we are given a function  $F$  from  $[(1 + \varepsilon)N^2]$  to the set of properly colored edges and its purported inverse  $G$  and we need to find  $x \in [(1 + \varepsilon)N^2]$  such that  $G(F(x)) \neq x$ . We arrive at the following problem:

**$c$ -AMGM-LC.** Let  $c > 1$  be a constant,  $V := [2N]$  and  $P := [c \cdot N^2]$ . The input is a coloring function  $C : V \rightarrow \{0, 1\}$  and two mappings  $F : P \rightarrow V \times V$ ,  $G : V \times V \rightarrow P$ . Let  $H := C^{-1}(0) \times C^{-1}(1)$ . The goal is to find solutions of either type:

- s1.** a pigeon  $x \in P$  such that  $G(F(x)) \neq x$ ; (Wrong Encoding-Decoding)
- s2.** a pigeon  $x \in P$  such that  $F(x) \notin H$ ; (Invalid Hole)

Indeed, it seems unclear how to massage a **LOSSY-CODE** instance of the shape  $[cN^2] \rightrightarrows H$  into a standard **LOSSY-CODE** instance of the form  $[2M] \rightrightarrows [M]$ , even though the AM-GM inequality implies that  $cN^2 \gg |H|$ . However, it turns out that such a reduction is possible (although highly non-trivial)! We encourage the reader to take a moment to think about how to reduce **AMGM-LC** to **LOSSY-CODE**.

**Theorem 1.10.** For every constant  $c > 1$ ,  **$c$ -AMGM-LC**  $\leq_{dt}$  **LOSSY-CODE**.

Our reduction goes through *bounded arithmetic*: We formalize the totality of  **$c$ -AMGM-LC** in Jeřábek’s theory **APC<sub>1</sub>** [Jeř07a], and Wilkie’s witnessing theorem for **APC<sub>1</sub>** [Tha02, Jeř04] implies a reduction from  **$c$ -AMGM-LC** to **LOSSY-CODE**. In particular, like every formalization in **APC<sub>1</sub>**, our reduction makes use of the *Nisan–Wigderson generator* [NW94].

Moreover, the techniques underlying **APC<sub>1</sub>** [Jeř07a] allow us to reduce problems to **LOSSY-CODE** in a *systematic* way; we provide two additional examples later ( **$c$ -Dual-AMGM-LC** in Section 6.2.2 and a problem capturing the Inclusion-Exclusion principle in Section 6.2.3). A secondary goal of expounding these reductions is to introduce the ideas of **APC<sub>1</sub>** to audiences who are less familiar with bounded arithmetic.

**Remark 1.11.** Unfortunately, it seems unclear how to formalize the totality of NEPHEW in  $\text{APC}_1$ , hence the bounded arithmetic approach does not seem to provide a reduction from NEPHEW to LOSSY-CODE. For example, our proof that  $\text{NEPHEW} \in \text{TFZPP}$  requires reasoning about the *level* of each node, which seems to be global reasoning that is infeasible in  $\text{APC}_1$ .

**Linear Ordering.** Finally, we consider one more natural problem in  $\text{TFZPP}$ . The Linear Ordering Principle has a storied history in proof complexity [Kri85, BG01, Pot20] and bounded arithmetic [CK98, Han04, BKT14, AT14]. It has been studied in the context of total search problems as well [KP24, HV25], where it was used in order to construct new algorithms for AVOID. A line of works in proof complexity [Rii01, AD08, Gry19, CdRN<sup>+</sup>23] has also considered a dense variant of this problem defined as follows, which lies in  $\text{TFZPP}$ .

**DENSE-LINEAR-ORDERING.** The input consists of the descriptions of a linear ordering  $\prec$  over  $N$  elements and a *median function*  $\text{med} : [N] \times [N] \rightarrow [N]$ . Without loss of generality, we may assume that for  $x \neq y \in [N]$ , exactly one of  $(x \prec y)$  and  $(y \prec x)$  is true, and that  $\text{med}(x, y) = \text{med}(y, x)$ . (That is,  $\prec$  is represented by a string of  $\binom{N}{2}$  bits and  $\text{med}$  is represented by a list of  $\binom{n}{2}$  elements in  $[N]$ .) A solution is one of the following.

- s1.**  $x, y, z \in [N]$  such that  $x \prec y$ ,  $y \prec z$ , and  $z \prec x$ ; or (Transitivity violation)
- s2.**  $x, y \in [N]$  such that  $x \prec y$ , but neither  $x \prec \text{med}(x, y)$  nor  $\text{med}(x, y) \prec y$ . (Invalid median)

While AVOID reduces to the Linear Ordering Principle [KP24], we show a converse in the dense setting.

**Theorem 1.12.**  $\text{DENSE-LINEAR-ORDERING} \leq_{dt} \text{LOSSY-CODE}$ .

## 2 Preliminaries

### 2.1 Basics of $\text{TFNP}$

$\text{TFNP}$  contains all search problems which are (i) total: a solution is guaranteed to exist, and (ii) in  $\text{NP}$ : there is an efficient procedure to check whether a candidate solution is valid. It is believed that  $\text{TFNP}$  does not admit complete problems [Pud15] and much of the research in this area has focused on studying syntactic subclasses (those with complete problems) which capture many of the total search problems of interest. These classes are typically defined by simple existence principles that capture the totality of the problems within that class. These naturally give rise to total search problems. For example,  $\text{PWPP}$  is the class of all search problems whose totality is witnessed by the existence principle: any map from  $2N$  to  $N$  must have a collision [Jeř16]. To make these problems non-trivial, the input is presented succinctly as a circuit  $C$  that on input  $i$  outputs the  $i$ -th bit of the search problem. For example, the existence principle for  $\text{PWPP}$  gives rise to the following (white-box) total search problem.

**WEAK-PIGEON.** Given  $P : \{0, 1\}^n \rightarrow \{0, 1\}^{n-1}$ , a solution is  $x \neq y$  such that  $P(x) = P(y)$ .

$\text{PWPP}$  is then the class of all total search problems which are efficiently reducible to WEAK-PIGEON.

A major thrust of this line of work is to understand the relationships between these classes. However, a separation between classes would imply  $\text{P} \neq \text{NP}$ . As a proxy, and as natural objects in their own right, researchers have studied total search problems in the *black-box* model. In this setting, the input  $C$  is given as a black box which can be queried, but we no longer have access to the description of  $C$ .

In this setting a *(query) search problem* is a sequence of relations  $R_n \subseteq \{0, 1\}^n \times \mathcal{O}_n$ , for each  $n \in \mathbb{N}$ . It is total if for every  $x \in \{0, 1\}^n$  there is  $o \in \mathcal{O}_n$  such that  $(x, o) \in R_n$ . We think of the input  $x \in \{0, 1\}^n$  as being accessed by querying the individual bits, and we will measure the complexity of solving  $R_n$  as the number of bits that must be queried to determine some suitable  $o \in \mathcal{O}_n$ . An efficient algorithm is one that makes at most  $\text{poly}(\log n)$ -many queries<sup>5</sup>; these problems belong to the class  $\text{FP}^{dt}$ , where  $dt$  indicates that it is the black-box version of the class. Similarly,  $R \in \text{TFNP}^{dt}$  if for every  $n \in \mathbb{N}$  and each  $o \in \mathcal{O}_n$  there exists a  $\text{poly}(\log n)$ -depth decision tree  $T_o : \{0, 1\}^n \rightarrow \{0, 1\}$  such that  $T_o(x) = 1$  iff  $(x, o) \in R_n$ . While search problems are formally defined as a sequence  $R = (R_n)_{n \in \mathbb{N}}$ , we will often want to speak about individual members of this sequence. For readability, we will abuse notation and refer to elements  $R_n$  in the sequence as total search problems. Furthermore, we will often drop the subscript  $n$  and rely on context to differentiate.

We compare the complexity of total search problems by reductions between them; the following is the black-box (decision tree) analogue of a deterministic polynomial-time reduction between search problems.

**Definition 2.1.** For total search problems  $R \subseteq \{0, 1\}^n \times \mathcal{O}_n$  and  $S \subseteq \{0, 1\}^m \times \mathcal{O}'_m$ , there is an  $S$ -formulation of  $R$  if for every  $i \in [m]$  and  $o \in \mathcal{O}'_m$  there are functions  $f_i : \{0, 1\}^n \rightarrow \{0, 1\}$  and  $g_o : \{0, 1\}^n \rightarrow \mathcal{O}_n$  such that

$$(f(x), o) \in S \implies (x, g_o(x)) \in R, \quad (2)$$

where  $f(x) := (f_1(x), \dots, f_m(x))$ . The *depth* of the  $S$ -formulation is

$$d := \max(\{\text{depth}(f_i) : i \in [m]\} \cup \{\text{depth}(g_o) : o \in \mathcal{O}'_m\}),$$

where  $\text{depth}(f)$  denotes the minimum depth of any decision tree which computes  $f$ . The *size* of the  $S$ -formulation is  $m$ , the number of input bits to  $S$ . The *complexity* of an  $S$ -formulation is  $\log m + d$  and the complexity of reducing  $R$  to  $S$  is the minimum complexity of any  $S$ -formulation of  $R$ .

This definition extends to sequences naturally. If  $S = (S_n)$  is a sequence and  $R_n$  is a single search problem, then the complexity of reducing  $R_n$  to  $S$  is the minimum over  $m$  of the complexity of reducing  $R_n$  to  $S_m$ . For two sequences  $S = (S_n)$  and  $R = (R_n)$ , the complexity of reducing  $R$  to  $S$  is the complexity of reducing  $R_n$  to  $S$  for each  $n$ . We say that a reduction from  $R$  to  $S$  is *efficient* if its complexity is  $\text{poly}(\log(n))$  and denote this by  $R \leq_{dt} S$ .

## 2.2 TFZPP

In this work, we will be particularly interested in the total search problems which are solvable in *randomized* polynomial time. Formally,  $R \subseteq \{0, 1\}^* \times \{0, 1\}^* \in \text{TFZPP}$  if there is a distribution  $\mathcal{D}$  over polynomial-time Turing Machines  $A$  with range  $\{0, 1, \perp\}$ , such that  $\Pr_{A \sim \mathcal{D}}[A(x) = \perp] \leq 1/3$  and

$\text{TFZPP}$  is defined semantically and it is unlikely to have complete problems. However, we show that it is exactly the  $\text{TFNP}$  problems in the  $\text{TF}\Sigma_2^P$  class  $\text{APEPP}$ , where  $\text{APEPP}$  is the class of total search problems that are reducible to  $\text{AVOID}$ , as defined in [KKMP21].

**Theorem 1.3.**  $\text{TFZPP} = \text{TFNP} \cap \text{APEPP}$ .

*Proof.* Let  $L \in \text{TFNP} \cap \text{APEPP}$ . This means that given an instance  $x$  of  $L$ , there are deterministic polynomial-time algorithms  $V$ ,  $C$ , and  $R$ , such that:

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<sup>5</sup>As the input is succinctly encoded, this corresponds to looking at a polynomial part of the entire input.

- **$V$  is a  $\text{TFNP}$  verifier for  $L$ .** For every string  $z$  of length polynomial in  $|x|$ ,  $V(x, z) = 1$  if and only if  $z$  is a valid solution for  $x$ .
- **$(C, R)$  is a reduction from  $x$  to  $\text{AVOID}$ .** The output of  $C(x)$  is a circuit  $C_x$  mapping  $\ell$  input bits to  $\ell + 1$  output bits, where  $\ell \leq \text{poly}(|x|)$ ; given any  $y \in \{0, 1\}^{\ell+1} \setminus \text{Range}(C_x)$ ,  $R(x, y)$  outputs a valid solution for  $x$ .

Then we can solve  $L$  in  $\text{TFZPP}$  via the following procedure. Guess  $y \in \{0, 1\}^{\ell+1}$  uniformly at random and compute  $z := R(x, y)$ . If  $V(x, z)$  accepts, then we output  $z$ ; otherwise, we output  $\perp$ . By the correctness of  $V$ , if we did not output  $\perp$ , then our output is a valid solution of  $x$ . On the other hand, since at least a  $1/2$  fraction of strings  $y \in \{0, 1\}^{\ell+1}$  are valid outputs of  $\text{AVOID}$  on the instance  $C_x$ , by the correctness of  $(R, C)$ , we will output a valid solution w.p. at least  $1/2$ .

Now we prove the converse direction. If  $L \in \text{TFZPP}$  then clearly  $L \in \text{TFNP}$ ; hence we only need to show that there is a mapping reduction from  $L$  to  $\text{AVOID}$ . Let  $U(x, r)$  be the zero-error randomized algorithm for  $L$ , i.e.,  $U(x, r)$  outputs a valid solution for  $x$  w.p. at least  $1/2$  over its randomness  $r$ , and it outputs  $\perp$  whenever it fails to output a valid solution.

By standard results in derandomization [NW94, IW97, Uma03], there exist absolute constants  $c, d \geq 1$  and a deterministic polynomial-time algorithm  $\text{PRG}$  such that the following holds. For every truth table  $f$  of length  $s^{10c}$ , if the circuit complexity of  $f$  is at least  $s^c$ , then  $\text{PRG}(f)$  outputs a list of  $s^d$  strings that  $(1/s^2)$ -fools every size- $s^2$  circuit. That is, for every circuit  $C : \{0, 1\}^s \rightarrow \{0, 1\}$  of size at most  $s^2$ ,

$$\left| \Pr_{x \sim \{0, 1\}^s} [C(x) = 1] - \Pr_{x \sim \text{PRG}(f)} [C(x) = 1] \right| \leq 1/s^2.$$

Now, let  $s \leq \text{poly}(|x|)$  be the circuit complexity of  $U$ . Consider the *truth table generator*  $\text{TT} : \{0, 1\}^{O(s^c \log s)} \rightarrow \{0, 1\}^{s^{10c}}$  that takes the description of a size- $s^c$  circuit  $C : \{0, 1\}^{10c \log s} \rightarrow \{0, 1\}$  as input and outputs the length- $s^{10c}$  truth table of  $C$ . We treat  $\text{TT}$  as an instance for  $\text{AVOID}$  and reduce  $x$  to  $\text{TT}$ .<sup>6</sup>

It remains to show how to solve the instance  $x$  deterministically given a non-output of  $\text{TT}$ . Note that if  $f \in \{0, 1\}^{s^{10c}}$  is a non-output of  $\text{TT}$ , then the circuit complexity of  $f$  is at least  $s^c$ , hence  $\text{PRG}(f)$  outputs a list of  $\text{poly}(s)$  strings that  $(1/s^2)$ -fools every size- $s^2$  circuits. This implies that

$$\Pr_{r \sim \text{PRG}(f)} [U(x, r) \neq \perp] \geq \Pr_{r \sim \{0, 1\}^s} [U(x, r) \neq \perp] - 1/s^2 \geq 1/2 - 1/s^2 > 0,$$

and in particular, there exists at least one string  $r \in \text{PRG}(f)$  such that  $U(x, r) \neq \perp$ . We can solve the instance  $x$  by cycling through every  $r \in \text{PRG}(f)$  and outputting  $U(x, r)$  whenever we encounter such a good  $r$ .  $\square$

Note that this equivalence holds even in the black-box model, since its proof is relativizing.

**Definition 2.2 (TFZPP).** A total NP search problem  $R \subseteq \{0, 1\}^* \times \{0, 1\}^*$  is in  $\text{TFZPP}$  if there is a distribution  $\mathcal{D}$  over polynomial-time algorithms  $A$  with output in  $\{0, 1, \perp\}$  such that:

1. For every  $x \in \{0, 1\}^*$  and every  $A \sim \mathcal{D}$ , if  $A(x) \neq \perp$  then  $(x, A(x)) \in R$ ,
2. For every  $x \in \{0, 1\}^*$ ,

$$\Pr_{A \sim \mathcal{D}} [A(x) = \perp] \leq 1/3.$$

Similarly,  $R \in \text{TFZPP}^{dt}$  if there is a family of distributions  $\mathcal{D} = \{\mathcal{D}_n\}_{n \in \mathbb{N}}$  over  $\text{poly} \log(n)$ -depth decision trees with leaves labeled in  $\{0, 1, \perp\}$ , where on input  $x$  we sample a decision tree  $A \sim \mathcal{D}_{|x|}$ , and  $\mathcal{D}$  satisfies (1) and (2).

<sup>6</sup>An unusual aspect of this reduction is that  $\text{TT}$  does *not* depend on  $x$ !

### 2.3 LOSSY-CODE

As mentioned in the introduction, LOSSY-CODE is the Herbrandization of AVOID. Let  $N < M$  be two parameters (think of  $N \ll M$ ), (the black-box version of) LOSSY-CODE is the following problem:

**LOSSY-CODE $_{N \rightarrow M}$ .** Given query access to a pair of functions  $f : [N] \rightarrow [M]$  and  $g : [M] \rightarrow [N]$ , find  $x \in [M]$  such that  $f(g(x)) \neq x$ .

We need the following basic fact about LOSSY-CODE that roughly states that the “stretch function” of LOSSY-CODE does not influence its complexity as long as it is in the “weak” regime. This fact and similar statements for other variants of the weak pigeonhole principle have been very useful in bounded arithmetic [PWW88, Tha02, Kra04, Jeř04, Jeř07a, CLO24], total search problems [Kor21, Kor22, LLR24], and cryptography [GGM86, Mer87].

**Lemma 2.3.** Let  $\varepsilon > 0$  and  $M > (1 + \varepsilon)N$ . There is a decision tree reduction of complexity  $O(\varepsilon^{-1} \log(M/N))$  from LOSSY-CODE $_{N \rightarrow (1+\varepsilon)N}$  to LOSSY-CODE $_{N \rightarrow M}$ .

By Lemma 2.3, LOSSY-CODE $_{N \rightarrow 1.01N}$ , LOSSY-CODE $_{N \rightarrow 2N}$ , and LOSSY-CODE $_{N \rightarrow N^{100}}$  are equivalent up to decision tree reductions of  $\text{polylog}(N)$  depth. In this paper, unless otherwise stated, LOSSY-CODE always stands for LOSSY-CODE $_{N \rightarrow 2N}$ .

We denote LOSSY as the class of total search problems reducible to LOSSY-CODE.<sup>7</sup> It follows from Lemma 2.3 that LOSSY is robust in the sense that it does not matter whether it is defined using LOSSY-CODE $_{N \rightarrow 1.01N}$  or LOSSY-CODE $_{N \rightarrow N^{100}}$  as the complete problem. In fact, LOSSY is *extremely* robust: it is closed under Turing reductions ( $\mathbf{FP}^{\text{LOSSY}} = \text{LOSSY}$  [BJ12, LPT24]) and it is self-low ( $\text{LOSSY}^{\text{LOSSY}} = \text{LOSSY}$  [GL25]).

We will also consider the *bijective* version of LOSSY-CODE, called BIJ-LOSSY-CODE. Let  $N < M$ , define:

**BIJ-LOSSY-CODE $_{N \rightarrow M}$ .** Given query access to a pair of functions  $f : [N] \rightarrow [M]$  and  $g : [M] \rightarrow [N]$ , find either  $x \in [M]$  such that  $f(g(x)) \neq x$ , or  $y \in [N]$  such that  $g(f(y)) \neq y$ .

Clearly, BIJ-LOSSY-CODE $_{N \rightarrow M}$  reduces to LOSSY-CODE $_{N \rightarrow M}$ . We also use BIJ-LOSSY-CODE to denote BIJ-LOSSY-CODE $_{N \rightarrow 2N}$  by default. It is not difficult to see that the “strong” versions of these problems, LOSSY-CODE $_{N \rightarrow N+1}$  and BIJ-LOSSY-CODE $_{N \rightarrow N+1}$ , are complete for PPADS and PPAD respectively.

## 3 Randomized Proof Complexity and Explicit Separations

We begin by describing the connection between black-box TFZPP and proof complexity, and how this can be leveraged to obtain explicit separations from other natural classes. Proof complexity is concerned with the efficient provability of propositional theorems (unsatisfiable CNF formulas) in various *proof systems*—simply a verifier for the language UNSAT of unsatisfiable CNF formulas.

**Definition 3.1.** A propositional proof system is a polynomial-time machine  $\mathcal{P}$  such that for every CNF formula  $F$ ,  $F \in \text{UNSAT}$  iff there exists a proof  $\Pi \in \{0, 1\}^*$  such that  $\mathcal{P}(F, \Pi) = 1$ . We say that  $\Pi$  is a  $\mathcal{P}$ -proof of  $F$  and define the size of  $\Pi$  to be  $s(\Pi) := |\Pi|$ .

When studying connections between proof systems and TFNP classes, it is standard to also consider an associated notion of the *width* of a proof  $w(\Pi)$ . This is typically specific to the proof

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<sup>7</sup>Previous literature [LPT24, CLMP25] defined LOSSY as the class of *decision problems* reducible to LOSSY-CODE. In our context, it is more natural to define LOSSY as a class of total search problems.

system—for example, in resolution (defined next), it is the maximum number of literals in a clause in  $\Pi$ , while for algebraic systems such as Sum-of-Squares, the width is the degree of the polynomials occurring in the proof.

With a definition of width, the *complexity* of proving  $F$  in  $\mathcal{P}$  is

$$\mathcal{P}(F) := \min_{\mathcal{P}\text{-proof } \Pi \text{ of } F} w(\Pi) + \log s(\Pi).$$

A standard example is the *resolution* proof system. A resolution proof of an unsatisfiable CNF formula  $F$  consists of a sequence of clauses  $C_1, \dots, C_t = \emptyset$  ending with the empty clause which contains no literals, such that each clause  $C_i$  either belongs to  $F$  or is derived from earlier clauses in the sequence according to the *resolution rule*.

**Resolution rule:** From two clauses with complementary literals  $A \vee x$  and  $B \vee \bar{x}$ , derive  $A \vee B$ .

The size of a resolution proof is the number of clauses that it contains, while the width is the maximum number of literals within any clause in the proof. A resolution proof  $C_1, \dots, C_t$  is *tree-like* if each  $C_i$  is used at most once as a premise for the resolution proof. They are named as such because the implication graph of such proofs is a tree.

There is a long line of work connecting proof complexity and black-box  $\text{TFNP}$  [BCE<sup>+</sup>98, GKRS19, GHJ<sup>+</sup>22, BFI23, FIM25, HKT24, Tha24, DR23, LPR24, FGPR24]. These connections show that a total search problem is contained within a class iff an associated proof system can prove the totality of that search problem. We can phrase the totality of any total search problem  $R \subseteq \{0, 1\}^n \times \mathcal{O}$  as an unsatisfiable CNF formula in the following way: for each  $o \in \mathcal{O}$  let  $V_o$  be a decision tree which checks whether  $o$  is a solution; that is,  $V_o(x) = 1$  iff  $(x, o) \in R$ . A root-to-leaf path in  $V_o$  is a *1-path* if its leaf is labeled 1. We will associate with any path  $p$  the conjunction of literals that it follows. Then the totality of  $R$  is expressed as

$$F_R := \neg \left( \bigvee_{o \in \mathcal{O}} \bigvee_{\text{1-path } p \in V_o} p \right).$$

If  $R \in \text{TFNP}^{dt}$  then  $V_o$  can be assumed to have depth  $\text{poly log}(n)$ , and hence the width of  $F_R$  is also  $\text{poly log}(n)$ .

Similarly, we can associate with any unsatisfiable CNF formula  $F = C_1 \wedge \dots \wedge C_m$  a total search problem  $\text{SEARCH}_F \subseteq \{0, 1\}^n \times [m]$  such that  $(x, o) \in \text{SEARCH}_F$  iff  $C_o(x) = 0$ . Observe that whenever  $F$  has  $\text{poly}(\log(n))$  width then  $\text{SEARCH}_F \in \text{TFNP}^{dt}$  and furthermore that  $\text{SEARCH}_F$  is reducible to  $R$  by decision trees of depth at most the width of  $F_R$ .

For a syntactic class  $\mathcal{C} \subseteq \text{TFNP}^{dt}$  we will denote by  $\mathcal{C}(R)$  the complexity of reducing  $R$  to  $S$ , where  $S$  is any complete problem for  $\mathcal{C}$ . We say that a proof system  $\mathcal{P}$  is *characterized* by a class  $\mathcal{C} \subseteq \text{TFNP}^{dt}$  if  $R \in \mathcal{C}$  iff  $\mathcal{P}(F) = \text{poly}(\mathcal{C}(R))$ . A standard example is that  $\text{FP}^{dt}$  characterizes tree-like resolution. Said differently, decision trees are equivalent to tree-like resolution proofs.

We extend these characterizations to capture randomized reductions. We show that randomized reductions between total search problems give rise to proofs in randomized proof systems, a notion introduced by Buss, Kołodziejczyk, and Thapen [BKT14].

**Definition 3.2.** Let  $\mathcal{P}$  be any propositional proof system. A *randomized  $\mathcal{P}$ -proof*, denoted  $r\mathcal{P}$ , of an unsatisfiable formula  $F$  is a distribution  $\mathcal{D}$  supported on pairs  $(\Pi, B)$ , such that

1. Each  $B$  is a CNF formula over the variables of  $F$ ,
2.  $\Pi$  is a  $\mathcal{P}$  proof of  $F \wedge B$ ,

3. For any assignment  $x \in \{0, 1\}^n$ ,  $\Pr_{(\Pi, B) \sim \mathcal{D}}[B(x) = 1] \geq 2/3$ .

The *size*  $s(\mathcal{D})$ , and *width*  $w(\mathcal{D})$  of an  $r\mathcal{P}$ -proof  $\mathcal{D}$  is the maximum width and size of a proof  $\Pi$  in the support of  $\mathcal{D}$ . The *complexity* of proving  $F$  in  $r\mathcal{P}$  is

$$r\mathcal{P}(F) := \min_{r\mathcal{P}-\text{proof } \mathcal{D} \text{ of } F} w(\mathcal{D}) + \log s(\mathcal{D})$$

Note that a randomized proof system is not a Cook-Reckhow proof system in the sense of [Definition 3.1](#) since its proofs typically cannot be polynomial-time verified [\[PT19\]](#).

The main theorem of this section, [Theorem 3.4](#), shows that a proof system  $\mathcal{P}$  is characterized by class  $\mathcal{C}$  iff the totality of the total search problems  $R$  which are randomly reducible to any complete problem for  $\mathcal{C}$  is provable in  $r\mathcal{P}$ . The following definition is equivalent to the probabilistic reduction in [\[Jeř16\]](#).

**Definition 3.3.** A randomized (ZPP) reduction from a search problem  $S \subseteq [t] \times \mathcal{O}$  to  $R \subseteq [n] \times \mathcal{Q}$  is a distribution  $\mathcal{D}$  over deterministic reductions  $\mathcal{T} = (T, \{T_o\})$  such that each output decision tree is labeled either by some  $j \in \mathcal{O}$  or by  $\perp$ , and  $\mathcal{D}$  satisfies

1. For every  $x \in [t]$  and every  $\mathcal{T} \sim \mathcal{D}$ , if  $(T(x), o) \in R$  then either  $T_o(x) = \perp$  or  $(x, T_o(x)) \in S$ .
2. For every  $x \in [t]$ ,

$$\Pr_{\mathcal{T} \sim \mathcal{D}} [\exists o \in \mathcal{O} : (T(x), o) \in R \wedge T_o(x) = \perp] \leq \varepsilon$$

**Theorem 3.4.** If a proof system  $\mathcal{P}$  is characterized by the total search problems reducible to  $R \in \text{TFNP}^{dt}$ , then  $r\mathcal{P}$  is characterized by the total search problems that are randomized-reducible to  $R$ .

The intuition for this theorem is most clear in the case of randomized reductions to  $\text{FP}^{dt}$  (which is  $\text{TFZPP}^{dt}$ ) and random tree-like resolution. This is also the case that we will use to derive consequences about  $\text{TFZPP}^{dt}$ . We leave the proof of [Theorem 3.4](#) to the [Appendix B](#).

We remark that [Theorem 3.4](#) reduces the task of showing that a  $\text{TFNP}$  class is closed under randomized reduction to showing that the corresponding proof system is *closed* in the sense that  $\mathcal{P} = r\mathcal{P}$ . We are not aware of any such proof system, and it would be interesting to exhibit one.

**Lemma 3.5.** There is a quasi-polynomial size random tree-like resolution proof of  $F = C_1 \wedge \dots \wedge C_m$  iff  $\text{Search}_F \in \text{TFZPP}^{dt}$ .

*Proof.* Suppose that  $\text{SEARCH}_F \in \text{TFZPP}^{dt}$  and let  $\mathcal{D}$  be a distribution over depth- $d$  decision trees solving  $\text{SEARCH}_F$  as in the definition of  $\text{TFZPP}^{dt}$ . We construct a  $\varepsilon$ -error randomized tree resolution proof  $\mathcal{P}$ , which is defined by the following sampling procedure:

1. Sample  $T \sim \mathcal{D}$ .
2. Let  $B$  be the set of clauses obtained by taking the negation of each root-to-leaf path in  $T$  ending in  $\perp$ ,

$$B := \{\neg p : p \in T \text{ is a root-to-}\perp \text{ path}\},$$

where we think of a path as the conjunctions of the literals that appear along it (a queried variable is a positive literal if  $p$  took the 1-branch, and a negative literal if  $p$  took the 0-branch).

3. To construct  $\Pi$ , we will use the equivalence between a decision tree solving the false-clause search problem and tree-resolution proofs. Let  $T^*$  be obtained from  $T$  by relabeling each path  $p$  ending in  $\perp$  by the clause  $\neg p \in B$ . Let  $F \cup B$  be the CNF formula whose clauses are the clauses of  $F$  and those in  $B$ , and observe that  $T^*$  is a depth- $d$  decision tree solving  $\text{SEARCH}_{F \cup B}$ . Thus, there is a depth- $d$  tree resolution proof  $\Pi$  of  $F \cup B$ .

As  $B$  states that we do not follow any root-to- $\perp$  path in  $T$ , for any  $x \in \{0, 1\}^n$ ,  $T(x) \neq \perp$  iff  $x$  satisfies all of  $B$ . Therefore,  $\Pr_{T \sim \mathcal{D}}[T(x) = \perp] \leq \varepsilon$  implies that  $\Pr_{(B, \Pi) \sim \mathcal{P}}[B(x) = 1] \geq 1 - \varepsilon$  for every  $x \in \{0, 1\}^n$ .

In the other direction, suppose that  $\mathcal{P}$  is a  $\varepsilon$ -random tree resolution proof of  $F$  with complexity  $c$ . We construct a distribution  $\mathcal{D}$  over decision trees solving  $\text{SEARCH}_F$  by the following sampling procedure:

1. Sample  $(\Pi, B) \sim \mathcal{P}$ .
2. Let  $T^*$  be the depth- $d$  decision tree solving  $\text{SEARCH}_{F \cup B}$  obtained from  $\Pi$  obtained by the equivalence between tree resolution proofs and decision trees in the same manner as in point (3) above. It is well-known that the depth of a resolution proof is bounded by its width, and hence  $T^*$  has depth at most  $c$ .
3. Let  $T$  be the decision tree obtained from  $T^*$  by relabeling each leaf of  $\Pi$  that is labeled by a clause in  $B$  by  $\perp$ .

As for any  $x \in \{0, 1\}^n$ ,  $\Pr_{(B, \Pi) \sim \mathcal{D}}[B(x) = 1] \geq 1 - \varepsilon$ , we have that  $\Pr_{T \sim \mathcal{D}}[T(x) = \perp] \leq \varepsilon$ .  $\square$

### 3.1 Separations

We now use [Lemma 3.5](#) to show that  $\text{TFZPP}^{dt}$  is not contained within any uniformly generated  $\text{TFNP}^{dt}$  class unless  $\text{NP}$  is contained within quasi-polynomial time (QP).

**Theorem 3.6.**  $\text{TFZPP}^{dt} \not\subseteq \mathcal{C}$  for any uniformly generated class  $\mathcal{C} \subseteq \text{TFNP}^{dt}$  unless  $\text{NP} \subseteq \text{QP}$ .

This theorem follows by combining the characterization of uniform  $\text{TFNP}^{dt}$  classes by proof systems of Buss et al. [\[BFI23\]](#), [Lemma 3.5](#), and the following result of Pudlák and Thapen [\[PT19\]](#).

This separation relies on a theorem of Pudlák and Thapen [\[PT19\]](#) who showed that random resolution cannot be simulated by any propositional proof system unless  $\text{P} \neq \text{NP}$ . A straightforward examination of their theorem reveals that it also holds for tree-like resolution and can be stated in the following form.

**Theorem 3.7** (Proposition 10 in [\[PT19\]](#)). There is a family of unsatisfiable 3-CNFs  $\mathcal{F}$  such that:

1. There are  $O(\log(n))$ -complexity random tree-like resolution proofs of  $\mathcal{F}$ .
2. If there is a propositional proof system which has  $\text{poly} \log(n)$ -complexity proofs of  $\mathcal{F}$  then  $\text{NP} \subseteq \text{QP}$ .

Indeed, to prove their theorem Pudlák and Thapen observe that random (treelike) resolution has small proofs of any highly unsatisfiable formula (one for which any assignment falsifies many clauses), and that the PCP theorem can be used to put any 3-CNF formula into this form (the family  $\mathcal{F}$ ). Using this, they show that if there existed a propositional proof system which could (quasi-polynomially) simulate random tree-like resolution, then one could use its variability to decide SAT.

Combining this theorem with [Lemma 3.5](#) and the characterization of  $\text{TFNP}^{dt}$  classes by propositional proof systems due to Buss et al. [\[BFI23\]](#) proves [Theorem 3.6](#). Say that  $R = \{R_n\} \in \text{TFNP}^{dt}$  is *uniformly generated* if there is a Turing Machine which on input  $1^n$  outputs  $R_n$ , and say that a class is uniformly generated if it has a uniformly generated complete problem. Note that all major  $\text{TFNP}^{dt}$  subclasses are uniformly generated.

*Proof of Theorem 3.6.* Let  $\mathcal{C}$  be a uniformly generated class such that  $\text{TFZPP}^{dt} \subseteq \mathcal{C}$ . Buss et al. [BFI23] showed that every uniformly generated  $\text{TFNP}^{dt}$  subclass is characterized by a proof system; let  $\mathcal{P}$  be the system for  $\mathcal{C}$ . Consider the family of formulas  $\mathcal{F}$  from Theorem 3.7. As  $\text{TFZPP}^{dt} \subseteq \mathcal{C}$ , there are  $\text{polylog}(n)$ -complexity  $\mathcal{P}$ -proofs of  $\mathcal{F}$ . Hence, Theorem 3.7 implies that  $\text{NP} \subseteq \text{QP}$ .  $\square$

### 3.2 Explicit Separations

The separating examples in Theorem 3.6 rely on an unproven hypothesis. We end this section by proving explicit separations between  $\text{TFZPP}^{dt}$  and every major  $\text{TFNP}^{dt}$  subclass which do not rely on any unproven assumptions. A separation of  $\text{PPA}^{dt}$  from  $\text{TFZPP}^{dt}$  was implicitly shown by Beame et. al. [BCE<sup>+</sup>98], who proved Nullstellensatz lower bounds for LOSSY-CODE.<sup>8</sup> The remaining major  $\text{TFNP}^{dt}$  classes are contained within  $\text{PLS}^{dt}$  and  $\text{PPP}^{dt}$ . We show the following.

**Theorem 3.8.** There exist explicit total search problems in  $\text{TFZPP}^{dt}$  which are not contained in  $\text{PLS}^{dt}$  nor  $\text{PPP}^{dt}$ .

It is known that if a total search problem  $\text{SEARCH}_F$  is in  $\text{PLS}^{dt}$  or  $\text{PPP}^{dt}$ , then  $F$  has a small low-degree *Sum-of-Squares* (SoS) proof; see [FKP19] for an exposition on this proof system. Our hard instance is based on the recent work of Hopkins and Lin [HL22], who exhibited the first explicit hard 3-XOR instance for SoS.

**Theorem 3.9** ([HL22]). There exist constants  $\mu_1, \mu_2 \in (0, 1)$  and a polynomial time algorithm which, given  $1^n$  as input, outputs a 3-XOR formula  $F = C_1 \wedge \dots \wedge C_m$  on  $n$  variables such that:

- For every  $x \in \{0, 1\}^n$ ,  $\Pr_{i \sim [m]}[C_i(x) = 1] \leq 1 - \mu_1$ .
- Any Sum-of-Squares refutation of  $F$  requires degree at least  $\mu_2 n$ .

*Proof of Theorem 3.8.* Let  $F$  be as in Theorem 3.9. We show that  $R := \text{SEARCH}_F$  satisfies the desired properties. We first prove  $R \in \text{TFZPP}^{dt}$ . Consider the following simple algorithm: sample  $i \sim [m]$  uniformly at random, and make three queries to check if  $C_i(x) = 0$ . If so, output  $i$ ; otherwise, output  $\perp$ . By the first item of Theorem 3.9, the algorithm succeeds with probability at least  $\mu_1$ . Repeating the procedure  $O(1/\mu_1)$  times boosts the success probability to at least  $2/3$ .

To separate  $R$  from  $\text{PPP}^{dt}$  and  $\text{PLS}^{dt}$ , we only need to show there is no efficient black-box reduction from  $R$  to a complete problem for one of these classes. If there was, then there would be an efficient SoS proof of  $F$ , contradicting the second item of Theorem 3.9.  $\square$

## 4 NEPHEW

Recall the NEPHEW problem, which is our main candidate for a total search problem in  $\text{TFZPP}$  but not reducible to LOSSY-CODE:

**NEPHEW.** Given a set  $V$  of vertices and two functions  $f : V \rightarrow V$  and  $g : V \rightarrow V$ . Think of  $f(v)$  as the *father* of  $v$  and  $g(v)$  as the *nephew* of  $v$ . A solution is one of the following.

**s1.**  $v \in V$  such that  $f(f(g(v))) \neq f(v)$  (your nephew's grandparent is not your parent)

<sup>8</sup>More specifically, Beame et. al. [BCE<sup>+</sup>98, Theorem 12] proved the Nullstellensatz degree lower bounds for WEAK-PIGEON. They also showed that any Nullstellensatz degree lower bounds for WEAK-PIGEON implies the same Nullstellensatz degree lower bounds for LOSSY-CODE in [BCE<sup>+</sup>98, Lemma 10] (see also Definition 3.1, 3.2 in [BCE<sup>+</sup>98] for the definition of LOSSY-CODE and WEAK-PIGEON).

**s2.**  $v \in V$  such that  $f(g(v)) = v$

(you are your nephew's parent)

The main result of this section is the inclusion theorem:

**Theorem 1.7.**  $\text{NEPHEW} \in \text{TFZPP} \cap \text{PWPP}$ .

The intuition behind [Theorem 1.7](#) is as follows:

- We can treat certain vertices in a NEPHEW instance like the root of a directed binary tree, where the leaves of the tree correspond to solutions of the NEPHEW instance.
- Finding a leaf of a rooted binary tree is easy for both PWPP and TFZPP computations.

Once we have proven the above, we are nearly done. First, choose an arbitrary vertex. Perhaps that vertex is one of the many that we can treat as the root of a binary tree, and so from it we can find a solution. Otherwise, we use a procedure to find such a root vertex. In fact, we will be able to find two vertices, one of which must be a good root vertex. To show inclusion in TFZPP, we just need to pick one of these two randomly. For PWPP, we will have to consider both. We make an adjustment to the argument for a single root vertex so that it works for two potential root vertices.

To be more concrete, we will reduce NEPHEW to the following *promise* search problem.

**LEAF-OF-ROOTED-TREE.** An instance consists of a set  $V$  of vertices, a special vertex  $v^*$ , and two functions  $L : V \rightarrow V \cup \{\perp\}$  and  $R : V \rightarrow V \cup \{\perp\}$ . We define a subset  $V^* \subseteq V$  recursively:  $v^* \in V^*$  and, for every  $v \in V^*$ , we add  $L(v)$  to  $V^*$  if  $L(v) \neq \perp$  and  $R(v)$  to  $V^*$  if  $R(v) \neq \perp$ . We promise that the induced subgraph on  $V^*$  is a (directed) tree rooted at  $v^*$  and that for all  $v \in V^*$  either:

- $L(v) = R(v) = \perp$ , or
- $L(v) \neq \perp$  and  $R(v) \neq \perp$  and  $L(v) \neq R(v)$ .

A solution is a  $(\lceil \log |V| \rceil + 1)$ -length path, represented by a string  $p \in \{L, R\}^{\lceil \log |V| \rceil + 1}$ , where starting at  $v^*$  and descending by the functions specified by the characters of  $p$  in order will at some point reach a vertex  $v$  where  $L(v) = R(v) = \perp$ .

Note that instead of simply asking for a leaf, we require a root-to-leaf path for a solution. This is to confirm that the leaf is in the binary tree rooted at  $v^*$ .

**Finding a root-to-leaf path in a rooted binary tree.** It is easy for a PWPP or TFZPP computation to find a solution to LEAF-OF-ROOTED-TREE. This follows from the simple observation that there are (many) more paths of length  $(\lceil \log |V| \rceil + 1)$  than vertices in the tree, so most paths must be solutions.

**Lemma 4.1.** A solution to LEAF-OF-ROOTED-TREE can be found with high probability using a randomized algorithm.

*Proof.* The algorithm guesses a random path of length  $\lceil \log |V| \rceil + 1$ , which will be a solution with probability at least  $5/6$ . This is because if a path  $p$  is not a solution, then following  $p$  reaches a vertex  $v_p$  with two children. The path  $p$  is the only non-solution path of length  $\lceil \log |V| \rceil + 1$  to reach  $v_p$ ; furthermore, because  $V^*$  is an induced tree, no other path ends at a vertex with  $L(v_p)$  or  $R(v_p)$  as children. This means that the set  $\{v_p, L(v_p), R(v_p)\}$  are uniquely reached by  $p$  out of all of the non-solution paths. Therefore, there are at least 3 times as many vertices in  $V$  as there are non-solution paths. Let the fraction of non-solution paths be  $\alpha$ . Then

$$|V| \geq 3\alpha \left| \{L, R\}^{\lceil \log |V| \rceil + 1} \right| \geq 3\alpha \cdot 2|V|,$$

and so  $\alpha \leq 1/6$ .  $\square$

To show inclusion in PWPP, we reduce to the PWPP-complete problem WEAK-PIGEON. (Note that this is not a reduction between TFNP problems, as LEAF-OF-ROOTED-TREE is a promise problem.) We recall its definition here:

**WEAK-PIGEON.** Given  $h : \{0, 1\}^n \rightarrow \{0, 1\}^{n-1}$  a solution is  $x \neq y$  such that  $h(x) = h(y)$ .

**Lemma 4.2.** LEAF-OF-ROOTED-TREE reduces to WEAK-PIGEON.

*Proof.* Let  $n = \lceil \log |V| \rceil + 1$ . Let  $v_p$  be the vertex reached by  $p$  if  $p$  is a non-solution path. Then we define  $h$  as a map from  $(\lceil \log |V| \rceil + 1)$ -length paths to vertices:

$$h(p) = \begin{cases} v_p & \text{if } p \text{ is not a solution;} \\ v^* & \text{otherwise.} \end{cases}$$

(Recall that since  $v^*$  is the root, we have that  $v_p \neq v^*$  for any path  $p$ .) Thus, paths  $(x, y)$  are a collision if and only if  $x$  and  $y$  are both solutions to LEAF-OF-ROOTED-TREE, and so from any collision we can find a solution to LEAF-OF-ROOTED-TREE by arbitrarily choosing one from the pair.  $\square$

**The structure of NEPHEW instances and finding a rooted binary tree.** For any NEPHEW instance  $(V, f, g)$ , let  $G_f$  be the directed graph with vertex set  $V$  and where  $(u, v)$  is an edge if and only if  $v = f(u)$ . Then  $G_f$  is a directed graph with out-degree one, and therefore the connected components of  $G_f$  have a simple structure: they are composed of a cycle (perhaps a self-loop) and trees (with edges oriented leaf-to-root) that are rooted at vertices in the cycle. For any vertex  $v \in V$ , define its *level* (denoted  $\ell(v)$ ) as the distance from  $v$  to any vertex on the cycle of its connected component. So, any vertex on the cycle has level 0, any non-cycle vertex pointing to a cycle vertex has level 1, and so on. See [Figure 2](#) for an illustration.

We give a reduction from NEPHEW to LEAF-OF-ROOTED-TREE under the assumption that we can find a vertex  $v^*$  with  $\ell(v^*) \geq 2$ . After proving this, the hard part will be finding such a vertex. The main component of this reduction is the procedure **Find-Children** ([Algorithm 1](#)), which is based on the functions  $f$  and  $g$  from an NEPHEW instance. Define **CheckSol**( $u$ ) to be the procedure that returns **True** iff  $u$  is a solution to the NEPHEW instance, that is, iff  $f(f(g(u))) \neq f(u)$  or  $f(g(u)) = u$ .

---

**Algorithm 1** Procedure **Find-Children** <sub>$f, g$</sub> ( $v$ )

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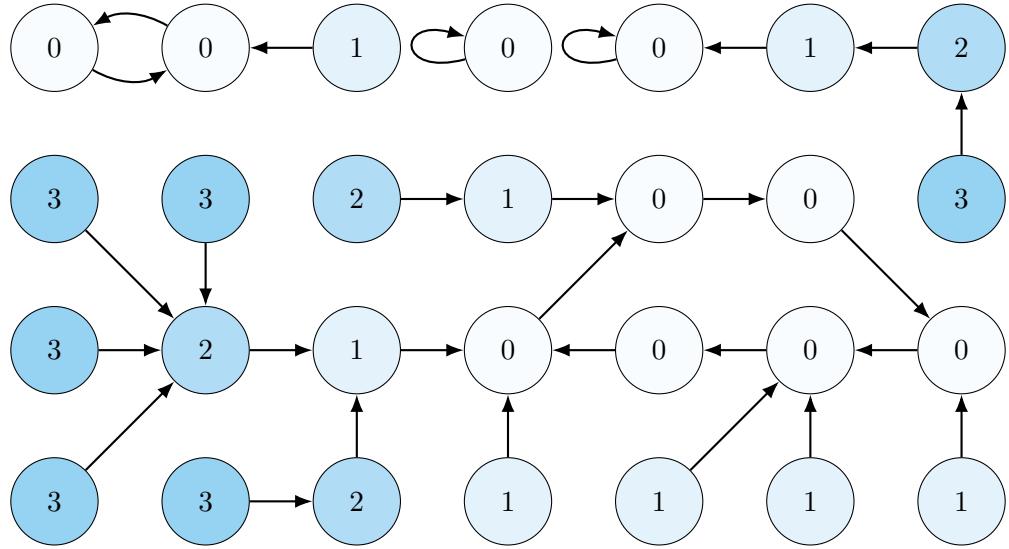
```

1:  $h(v) \leftarrow g(f(g(v)))$  ▷ Rename for notational brevity
2: if CheckSol( $v$ )  $\vee$  CheckSol( $g(v)$ )  $\vee$  CheckSol( $f(g(v))$ )  $\vee$  CheckSol( $h(v)$ ) then
3:   return ( $\perp, \perp$ ) ▷ We have found a solution, so we can stop here
4: else
5:   return ( $g(v), h(v)$ )

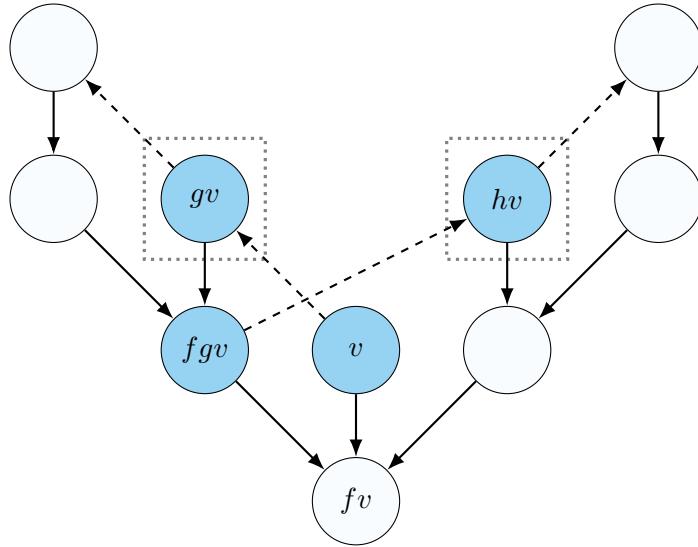
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See [Figure 3](#) for an illustration. The idea is to construct the tree by defining the left and right children of  $v$  to be two nodes reachable from  $v$ , unless the procedure finds a nearby solution, in which case we can make  $v$  into a leaf, as it is easy to compute a solution given  $v$ .



**Figure 2:** An example  $G_f$  with levels marked.



**Figure 3:** The procedure performed by  $\text{Find-Children}_{f,g}(v)$ . Solid arrows represent  $f$  and dashed arrows represent  $g$ . Parentheses are omitted in labels. The dotted boxes indicate that vertices  $g(v)$  and  $h(v)$  will be returned as the children of  $v$ . The procedure will check if the shaded vertices are NEPHEW solutions, and in doing so will visit the unshaded vertices (but will not detect if these are solutions). Note that  $f(h(v)) = v$  is possible, but  $f(h(v)) = f(g(v))$  is not.

Although the intuition behind the reduction is straightforward, some work needs to be done to show that `Find-Children` gives a valid binary tree. The following properties will help.

**Lemma 4.3.** Let  $\text{Find-Children}_{f,g}(v) = (a, b)$ . If  $(a, b) \neq (\perp, \perp)$ , then

- (i)  $a \neq b$ ,
- (ii)  $f(a) \neq f(b)$ ,
- (iii)  $f(f(a)) = f(f(b)) = f(v)$ , and
- (iv) if  $\ell(v) \geq 2$ , then  $\ell(a) = \ell(b) = \ell(v) + 1$ .

*Proof.*

- (i) Since  $(a, b) \neq (\perp, \perp)$ , we have that  $f(g(v)) = f(a)$  is not an NEPHEW solution, and in particular  $f(g(f(a))) \neq f(a)$ . This means that  $a \neq b$ , as  $b = g(f(a))$ .
- (ii) As  $f(g(v))$  is not a solution, applying  $f(g(u)) \neq u$  to  $u = f(g(v))$  gives  $f(b) = f(g(f(g(v)))) \neq f(g(v)) = f(a)$ .
- (iii) As  $v$  is not a solution,  $f(f(a)) = f(f(g(v))) = f(v)$ . As  $f(g(v))$  is not a solution, applying  $f(f(g(u))) = f(u)$  for  $u = f(g(v))$  gives  $f(f(b)) = f(f(g(f(g(v)))) = f(f(g(v))) = f(v)$ .
- (iv) Under the assumption that  $\ell(v) \geq 2$ , we know that  $\ell(f(v)) = \ell(v) - 1 > 0$ , which implies that any vertex with  $f(f(u)) = f(v)$  has  $\ell(u) = \ell(f(v)) + 2 = \ell(v) + 1$ . By [Item \(iii\)](#), this applies to  $a$  and  $b$ .  $\square$

**Remark 4.4.** [Lemma 4.3 \(iv\)](#) does not hold without the hypothesis  $\ell(v) \geq 2$ , as if  $\ell(f(v)) = 0$  there is no guarantee that vertices with edges pointing to  $f(v)$  have level greater than 0. This is why it is necessary to assume  $\ell(v^*) \geq 2$  for the simple reduction given here.

**Lemma 4.5.** Let  $(V, f, g)$  be an instance of NEPHEW. Then define  $L$  and  $R$  by

$$(L(v), R(v)) \leftarrow \text{Find-Children}_{f,g}(v).$$

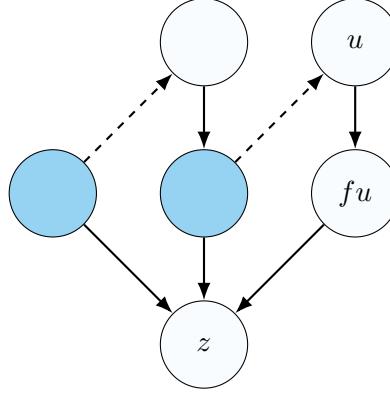
Given  $v^* \in V$  with  $\ell(v^*) \geq 2$ ,  $(V, v^*, L, R)$  is a valid instance to LEAF-OF-ROOTED-TREE.

*Proof.* All we need to show is that  $v^*$  is the root of an induced tree. Recall that  $V^*$  denotes the set of vertices reachable from  $v^*$  via  $L$  and  $R$  (i.e., using edges of the form  $(u \rightarrow L(u))$  and  $(u \rightarrow R(u))$ ). By [Lemma 4.3 \(iv\)](#), the induced subgraph on  $V^*$  can be assigned levels such that edges are directed only from lower levels to higher levels, i.e. it is a DAG. By [Lemma 4.3 \(i\)](#), the DAG has outdegree 2. To prove this induced DAG is indeed a tree, it suffices to show that no two vertices share the same child. Indeed, if there are vertices  $u, u' \in V^*$  such that  $\{L(u), R(u)\} \cap \{L(u'), R(u')\} \neq \emptyset$ , then by [Lemma 4.3 \(iii\)](#), we have  $f(u) = f(u')$ . Hence, it suffices to prove the following claim:

**Claim 4.6.** If  $u, u' \in V^*$  are two different vertices, then  $f(u) \neq f(u')$ .

*Proof of Claim 4.6.* We may assume that  $\ell(u) = \ell(u')$ , as otherwise  $f(u) \neq f(u')$  by the observation about levels in  $V^*$ . The proof is by induction on levels. At level  $\ell(v^*)$ , there is only one vertex, hence the base case is trivially true. Assume that at level  $k$  (where  $k \geq \ell(v^*)$ ), no two vertices in  $V^*$  map via  $f$  to the same vertex. We will prove that it also holds for level  $k + 1$ .

For two different vertices  $u, u'$  with  $\ell(u) = \ell(u') = k + 1$ , we may assume  $u$  and  $u'$  are the children of two different vertices in  $V^*$ : if they are children of the same vertex, by [Lemma 4.3 \(ii\)](#)  $\{u, u'\} = \{L(w), R(w)\}$  implies  $f(u) \neq f(u')$  and we are done. So, let  $w \neq w'$  be such that



**Figure 4:** The argument behind [Claim 4.6](#). Solid arrows represent  $f$  and dashed arrows represent  $g$ . Parentheses are omitted in labels. The shaded vertices are possible locations of the  $w \in V^*$  such that either  $L(w) = u$  or  $R(w) = u$ .

$u \in \{L(w), R(w)\}$  and  $u' \in \{L(w'), R(w')\}$ . Then  $\ell(w) = \ell(w') = k$  and by the inductive hypothesis  $f(w) \neq f(w')$ .

Assume that  $f(u) = f(u')$ . We will prove shortly that all vertices in  $V^*$  that map to  $u$  or  $u'$  by  $L$  or  $R$  map to some common vertex  $z$  by  $f$ , a contradiction with  $f(w) \neq f(w')$ . Indeed, set  $z = f(f(u)) = f(f(u'))$ . If a vertex  $x \in V^*$  has  $L(x) = g(x) = u$  (the same arguments will apply to  $x$  that maps to  $u'$ ), then

$$z = f(f(u)) = f(f(g(x))) = f(x).$$

If a vertex  $x \in V^*$  has  $R(x) = g(f(g(x))) = u$ , then

$$z = f(f(u)) = f(f(g(f(g(x))))) = f(f(g(x))) = f(x),$$

where we have applied  $f(f(g(y))) = f(y)$  to  $y = f(g(x))$  which we know is not a NEPHEW solution because it was checked by **Find-Children**.  $\diamond$

See [Figure 4](#) for an illustration of the argument behind [Claim 4.6](#).  $\square$

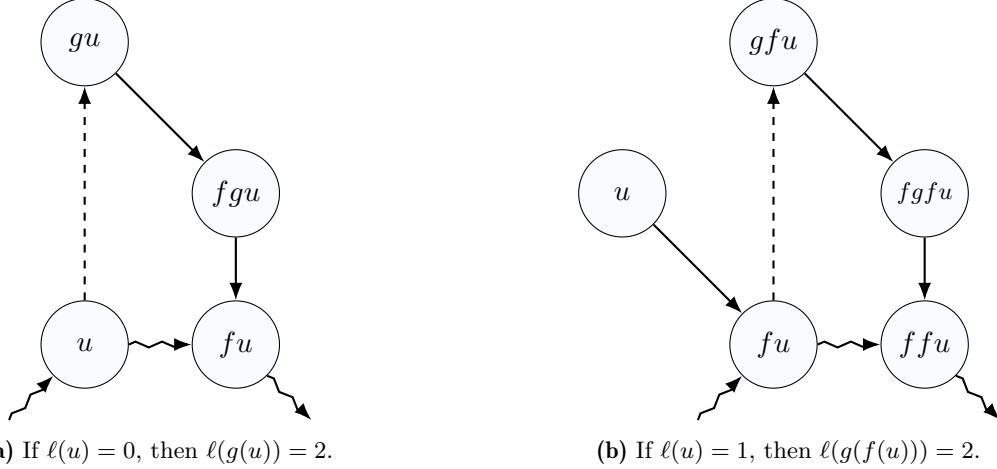
**Completing the argument.** It remains to find a vertex  $v^*$  with  $\ell(v^*) \geq 2$ . We do not know how to achieve this deterministically; instead, we will find a pair of vertices  $(v, v')$  such that *either*  $\ell(v) \geq 2$  or  $\ell(v') \geq 2$ .

**Lemma 4.7.** Let  $u \in V$  be an arbitrary starting vertex. Let  $v = g(u)$  and  $v' = g(f(u))$ . Then either

- at least one of  $\{u, v, v'\}$  is a solution, or
- at least one of  $\{v, v'\}$  is at level at least 2.

*Proof.* Assume that there are no solutions among  $\{u, v, v'\}$ . There are three cases:

- **Case I:** Suppose that  $\ell(u) = 0$ . We claim that  $\ell(v) = 2$  in this case. Indeed,  $u$  is the only vertex at level 0 that maps via  $f$  to  $f(u)$ . Since  $f(f(v)) = f(f(g(u))) = f(u)$  but  $f(v) = f(g(u)) \neq u$ ,  $f(v)$  has to be at level 1, hence  $v$  is at level 2.
- **Case II:** Suppose that  $\ell(u) = 1$ . In this case, we have  $\ell(f(u)) = 0$ , hence the same argument as above applies to show that  $v' = g(f(u))$  is at level 2.



**Figure 5:** Illustration of cases I and II of [Lemma 4.7](#). Solid arrows represent  $f$  and dashed arrows represent  $g$ . Zigzag  $f$  arrows are between vertices of level 0. Parentheses are omitted in labels.

- **Case III:** Suppose that  $\ell(u) \geq 2$ . In this case,  $f(u)$  is at level at least 1. Since  $f(f(v)) = f(f(g(u))) = f(u)$ , we have that  $v$  is at level at least 2.  $\square$

See [Figure 5](#) for an illustration of cases I and II of [Lemma 4.7](#).

Now we are ready to prove our main results. Recall the statement of [Theorem 1.7](#):

**Theorem 1.7.**  $\text{NEPHEW} \in \text{TFZPP} \cap \text{PWPP}$ .

*Proof.* The proof of  $\text{NEPHEW} \in \text{TFZPP}$  is easy. Pick an arbitrary vertex  $u$  and define  $v = g(u)$  and  $v' = g(f(u))$ . By [Lemma 4.7](#), if none of  $u, v, v'$  are solutions of  $\text{NEPHEW}$ , then at least one of  $v$  and  $v'$  is at level at least 2. Therefore, we can randomly select one vertex in  $\{v, v'\}$  as the root  $v^*$  and run the randomized algorithm for **LEAF-OF-ROOTED-TREE** on the instance  $(V, v^*, L, R)$ . The correctness is guaranteed by [Lemma 4.5](#).

Now we prove that  $\text{NEPHEW} \in \text{PWPP}$ . Intuitively, we will run the reduction of [Lemma 4.5](#) in parallel on (the direct product of) two graphs where the root is  $v$  in one graph and is  $v'$  in the other. Because we can only guarantee that our starting point is at level  $\geq 2$  in only one of these graphs, we only know that one of the graphs has an induced tree rooted at its respective starting point by the reduction process. Fortunately, the overall graph on  $V \times V$  will have a rooted induced tree.

By [Lemma 4.7](#), starting with an arbitrary vertex, we can obtain either a  $\text{NEPHEW}$  solution (in which case we are done) or a pair  $(v, v')$  where at least one is at level at least 2. We will reduce to **LEAF-OF-ROOTED-TREE** on the vertex set  $V \times V$ . Set

$$(A(u, u'), B(u, u')) \leftarrow \text{Find-Children}_{f,g}(u),$$

$$(C(u, u'), D(u, u')) \leftarrow \text{Find-Children}_{f,g}(u').$$

Set  $L(u, u') = (A(u, u'), C(u, u'))$ , unless one of  $A(u, u'), C(u, u')$  is  $\perp$ , in which case  $L(u, u') = \perp$ . Set  $R(u, u') = (B(u, u'), D(u, u'))$ , again unless one side of the pair is  $\perp$  in which case  $R(u, u') = \perp$ . By the construction of **Find-Children**, if one of  $L, R$  is set to  $\perp$  the other one will as well. The special vertex in  $V \times V$  will be  $(v, v')$ .

Then  $V^* \subset V \times V$  induces a binary tree (recall that  $V^*$  is the set of vertices reachable from  $(v, v')$  by  $L, R$ ). Say that  $\ell(v) \geq 2$ ; the other case follows by symmetry. Starting at  $(v, v')$ ,  $L$  and  $R$  will yield a tree structure on the first member of the pair by the same argument as [Lemma 4.5](#).

Let  $p, p'$  be two distinct paths of any length which start at  $(v, v')$  and traverse with  $L$  and  $R$ . The vertex reached by  $p$  will have a different first pair element than the vertex reached by  $p'$  (by the tree structure on the first element of the pair), and thus  $p$  and  $p'$  arrive at distinct vertices. This means that there are no (undirected) cycles in the induced graph on  $V^*$ , and so it is a tree.  $\square$

## 5 Finding a Leaf in a Binary Tree

In the previous section, we reduced NEPHEW to the promise problem LEAF-OF-ROOTED-TREE, which captures the following principle:

*Randomly walking down a binary tree will reach a leaf in logarithmic time in expectation.*

In this section, we study a family of *total* (instead of promise) search problems that capture the same principle. We then study the power of these search problems.

The problem EMPTY-CHILD captures the task of finding a leaf in a tree where each non-leaf vertex  $v$  has at least two different children  $L(v)$  and  $R(v)$ . This is made total (i.e. we do not need the promises as in LEAF-OF-ROOTED-TREE) by adding a parent function, denoted  $F(v)$ .

**EMPTY-CHILD.** The input is a set of vertices  $V$  and three functions  $F, L, R : V \rightarrow V$ , where  $F(u)$  is the father of  $u$ , and  $L(u), R(u)$  are the left and the right child of  $u$ , respectively. There are two possible solutions:

- s1.  $u \in V$  such that  $F(L(u)) \neq u$  or  $F(R(u)) \neq u$  or  $L(u) = R(u) \neq u$ . (Empty Child)
- s2. 1, if  $L(1) = 1$  or  $R(1) = 1$  or  $F(1) \neq 1$ . (Wrong Root)

**Intuition behind EMPTY-CHILD.** We think of EMPTY-CHILD as defining a directed graph on  $V$ . Draw an edge from  $v$  to  $w$  if  $F(w) = v$  and either  $L(v) = w$  or  $R(v) = w$ . If  $v$  does not point to two distinct vertices in this graph, then  $v$  has an “empty child” and  $v$  is a leaf<sup>9</sup> of the graph.

The directed graph defined above may have multiple connected components. They will be of the following sorts:

- Isolated vertices. We may have  $F(v) = L(v) = R(v) = v$ .
- Trees.
- Cycles with trees rooted at each node in the cycle.

Unless there is a solution of type (Wrong Root), we are forced to have at least one tree, rooted at vertex 1. This forces the graph to have structures other than just isolated vertices. Then we can find a leaf of that tree using the principle captured by LEAF-OF-ROOTED-TREE. An important observation is that in the third type of structure—cycles with trees—walking randomly will also reach a leaf in logarithmic time. We will show shortly that solution (Wrong Root) can be relaxed to allow for graphs without trees, as long as at least one cycle-with-trees is present.

In EMPTY-CHILD, it is possible that there are vertices  $v, w$  such that  $F(w) = v$  but  $L(v) \neq w$  and  $R(v) \neq w$ . This is fine: structurally, we can interpret  $w$  as being the root of a new tree. We will consider a variant of EMPTY-CHILD where such a situation is forbidden.

In LEAF-OF-ROOTED-TREE, we needed a root-to-leaf path to prove that the leaf vertex was in the promised tree. In contrast, here we enforce the tree structure syntactically, and hence do not require a path. Indeed, a solution to EMPTY-CHILD need not be in the connected component that contains the canonical root vertex.

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<sup>9</sup>We slightly stretch the definition of leaf to include vertices with only one child. Equivalently, we could redefine the graph such that a vertex may only have two or zero children.

**Results about EMPTY-CHILD.** The main result of this section is the LOSSY-completeness of EMPTY-CHILD:

**Theorem 5.1.** EMPTY-CHILD is equivalent to LOSSY-CODE.

The problem from the previous section, NEPHEW, is at least as strong as EMPTY-CHILD: we give a reduction in [Section 5.4](#). We conjecture that NEPHEW is strictly more powerful than EMPTY-CHILD. A variant of NEPHEW is considered in [Section 5.5](#) and is shown to be equivalent to EMPTY-CHILD.

**Variants of EMPTY-CHILD.** For a proof later in this section it will be useful to weaken [\(Wrong Root\)](#). Instead of enforcing that a *root* vertex exists, we only enforce that an *internal* vertex that is not a self-loop exists.

**EMPTY-CHILD'.** Given the same inputs as in EMPTY-CHILD, we accept the solutions [\(Empty Child\)](#) and:

**s2a.** 1, if  $L(1) = 1$  or  $R(1) = 1$ . [\(Wrong Internal Vertex\)](#)

It turns out that EMPTY-CHILD' is equivalent to EMPTY-CHILD in terms of decision tree reductions, but we do not know of a direct way to prove this. Instead, we will use LOSSY-CODE as an intermediate step in the reduction.

**Theorem 5.2.** EMPTY-CHILD and EMPTY-CHILD' are equivalent under black-box reductions.

It is easy to see that EMPTY-CHILD reduces to EMPTY-CHILD', as the difference between the two is just a weakening of one of the solutions. In [Section 5.1](#), we will prove that EMPTY-CHILD' reduces to LOSSY-CODE ([Lemma 5.3](#)). In [Section 5.3](#), we will prove that LOSSY-CODE reduces to EMPTY-CHILD ([Theorem 5.9](#)), completing the proof of [Theorem 5.2](#).

We also consider a stricter variant where the  $F$  function and the  $L$  and  $R$  functions are required to “agree”:

**BINARY-EMPTY-CHILD.** Given the same inputs as in EMPTY-CHILD but in addition to [\(Empty Child\)](#) and [\(Wrong Root\)](#), we also accept the following solution:

**s3.** a vertex  $u \in V \setminus \{1\}$  such that  $u \notin \{L(F(u)), R(F(u))\}$ . [\(Wrong Father\)](#)

Finally, we will consider variants of EMPTY-CHILD with added *height* functions in [Section 5.2](#). The analysis of these will be a warm-up for the proof that LOSSY-CODE reduces to EMPTY-CHILD in [Section 5.3](#).

## 5.1 EMPTY-CHILD reduces to LOSSY-CODE

It is easy to see that EMPTY-CHILD is in TFZPP: Start from the root 1 and walk down the tree using  $L$  or  $R$  randomly until we reach a leaf. In fact, the same proof reduces EMPTY-CHILD (in fact, also EMPTY-CHILD') to LOSSY-CODE:

**Lemma 5.3.** EMPTY-CHILD' reduces to LOSSY-CODE via a black-box reduction.

*Proof.* Consider an instance of EMPTY-CHILD'  $(V, F, L, R)$  and let  $\ell := \lceil \log |V| \rceil$ . We construct a LOSSY-CODE instance  $(f, g)$  with  $N := 2^\ell$ . Intuitively,  $f : [2N] \rightarrow [N]$  maps a tree-path of length  $\ell + 1$  to a vertex in  $u$  by travelling downwards in the tree, and  $g : [N] \rightarrow [2N]$  maps a vertex in  $V$  to a tree-path by travelling upwards.

More formally, identify  $[2N]$  with  $\{\text{L}, \text{R}\}^{\ell+1}$ , the space of length- $(\ell + 1)$  strings over the alphabet  $\{\text{L}, \text{R}\}$ . Every such string  $x \in \{\text{L}, \text{R}\}^{\ell+1}$  corresponds to a path of length  $\ell + 1$  starting from the root: Let  $v_0 := 1$  be the root and for each  $i \geq 1$ ,

$$v_i := \begin{cases} L(v_{i-1}) & \text{if } x_i = \text{L}; \\ R(v_{i-1}) & \text{if } x_i = \text{R}. \end{cases}$$

Then,  $x$  corresponds to the path  $p_x := (v_0, v_1, \dots, v_{\ell+1})$ . We define  $f(x)$  to be  $v_{\ell+1}$ , the endpoint of this path. For instance,  $f(\text{LLR}) = R(L(L(1)))$  when  $\ell = 2$ .

Conversely, for any  $u \in [N]$ , we can construct a string  $x \in \{\text{L}, \text{R}\}^{\ell+1}$  by traversing  $\ell + 1$  steps upwards from  $u$ : in the  $i$ -th step, we set  $x_{\ell+2-i} \leftarrow \text{L}$  if  $u = L(F(u))$ , or  $x_{\ell+2-i} \leftarrow \text{R}$  otherwise<sup>10</sup>; then update  $u \leftarrow F(u)$ . We set  $g(u) = x$ .

Now we prove the correctness of the reduction. Let  $x \in [2N]$  be such that  $g(f(x)) \neq x$ , we use a case analysis to find a solution of **EMPTY-CHILD'** from  $x$ . First we find the path  $p_x = (v_0, v_1, \dots, v_{\ell+1})$  as defined above. Normally, two adjacent vertices in the path should be distinct (since a node should be different from its child); we deal with the abnormal case before proceeding. Suppose there exists some  $i \geq 0$  such that  $v_i = v_{i+1}$ , and let  $i$  be the smallest such index.

- If  $i = 0$ , then either  $L(1) = 1$  or  $R(1) = 1$ , hence 1 is a (**Wrong Internal Vertex**).
- Otherwise, we have  $v_{i-1} \neq v_i$ . Without loss of generality, let us assume that  $v_i = L(v_{i-1})$  and  $v_{i+1} = L(v_i) (= v_i)$ ; the cases where we walk down the right child are completely symmetric.
  - If  $F(v_i) \neq v_{i-1}$ , then  $F(L(v_{i-1})) \neq v_{i-1}$  and hence  $v_{i-1}$  has an (**Empty Child**).
  - Otherwise,  $F(L(v_i)) = F(v_i) = v_{i-1} \neq v_i$  and hence  $v_i$  has an (**Empty Child**).

Now we are in the “normal” case where for every  $i \geq 0$ ,  $v_i \neq v_{i+1}$ . Let  $x' := g(f(x))$ . Recall that the precise definition of  $x'$  is as follows: let  $u_{\ell+1} := v_{\ell+1} (= f(x))$ , and let  $u_i := F(u_{i+1})$  for each  $i$  from  $\ell$  down to 0, then  $x'_i = 0$  if  $u_i = L(F(u_i))$  and  $x'_i = 1$  otherwise.

Let  $i$  be the largest index such that either  $x'_i \neq x_i$  or  $v_{i-1} \neq u_{i-1}$ . (Note that such  $i$  exists because  $x' = g(f(x)) \neq x$ .) Then  $v_i = u_i$ . We claim that  $v_{i-1}$  has an (**Empty Child**), which would finish the proof.

- If  $v_{i-1} \neq u_{i-1} = F(v_i)$ , then  $v_{i-1} \neq F(L(v_{i-1}))$  or  $v_{i-1} \neq F(R(v_{i-1}))$  depending on whether  $x_i$  is 0 or 1. In either case,  $v_{i-1}$  has an (**Empty Child**).
- If  $x_i = 0$  and  $x'_i = 1$ , then  $v_i = L(v_{i-1})$  but  $u_i \neq L(F(u_i))$  (hence  $v_i \neq L(F(v_i))$ ). Note that this implies that  $v_{i-1} \neq F(v_i)$ , hence  $F(L(v_{i-1})) = F(v_i) \neq v_{i-1}$  and  $v_{i-1}$  has an (**Empty Child**).
- If  $x_i = 1$  and  $x'_i = 0$ , then  $v_i = R(v_{i-1})$  but  $u_i = L(F(u_i))$  (hence  $v_i = L(F(v_i))$ ). This implies that  $F(R(v_{i-1})) = F(v_i)$ . If  $F(v_i) \neq v_{i-1}$ , then  $v_{i-1}$  has an (**Empty Child**). Otherwise we have  $L(v_{i-1}) = R(v_{i-1}) = v_i$  and  $v_{i-1} \neq v_i$  (by the reasoning above) and  $v_{i-1}$  has an (**Empty Child**).  $\square$

## 5.2 Finding a Leaf with Heights

Before showing that **EMPTY-CHILD** is complete for **LOSSY**, we take a detour to study variants of **EMPTY-CHILD** with *heights*. Indeed, the proof that **EMPTY-CHILD** is **LOSSY**-complete is inspired by the investigations of these variants. We first define the variants of **EMPTY-CHILD** and **BINARY-EMPTY-CHILD** with heights:

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<sup>10</sup>It is possible that  $u \notin \{L(F(u)), R(F(u))\}$ .

**EMPTY-CHILD-W-HEIGHT.** The input is a set  $V$  of vertices and four functions  $F, L, R : V \rightarrow V, H : V \rightarrow [|V|]$ . Besides **(Empty Child)** and **(Wrong Root)** listed in the definition of EMPTY-CHILD, the following solution is also valid:

s4. a vertex  $u \in V \setminus \{1\}$  such that  $u \neq F(u)$  and  $H(u) \neq H(F(u)) + 1$ ; or 1, if  $H(1) \neq 1$ . **(Wrong Height)**

**BINARY-EMPTY-CHILD-W-HEIGHT.** All of **(Empty Child)**, **(Wrong Root)**, **(Wrong Father)**, and **(Wrong Height)** are valid solutions.

Again, we remark that an isolated vertex  $u$  with  $F(u) = L(u) = R(u) = u$  is *not* a solution of EMPTY-CHILD-W-HEIGHT or BINARY-EMPTY-CHILD-W-HEIGHT.

Due to the presence of heights, these problems are in PLS now:

**Lemma 5.4.** EMPTY-CHILD-W-HEIGHT is in PLS, and therefore, SOPL.

*Proof.* We reduce the EMPTY-CHILD-W-HEIGHT instance to the instance of SINK-OF-DAG where for each node  $v \in V$ , the successor of  $v$  is  $L(v)$  and the potential of  $v$  is  $H(v)$ . Let  $v$  be a solution of SINK-OF-DAG, then one of the following cases happens:

- $v = 1$  and  $L(v) = 1$ . Then 1 is a **(Wrong Root)**.
- $L(v) \neq v$  and  $L(L(v)) = L(v)$ . This implies that either  $F(L(v)) \neq v$  or  $F(L(L(v))) \neq L(v)$ , hence either  $v$  or  $L(v)$  is a node with **(Empty Child)**.
- $L(v) \neq v$  and  $H(L(v)) \leq H(v)$ . If  $F(L(v)) \neq v$  then  $v$  is a node with **(Empty Child)**. Otherwise, let  $u := L(v)$ , we have that  $u \neq F(u) = v$  and that  $H(u) \leq H(F(u))$ , hence  $u$  has **(Wrong Height)**.

Therefore, EMPTY-CHILD-W-HEIGHT reduces to SINK-OF-DAG and is in PLS. Finally, since EMPTY-CHILD-W-HEIGHT is also in LOSSY  $\subseteq$  PPADS, it is in SOPL = PLS  $\cap$  PPADS [GHJ<sup>+</sup>24].  $\square$

In contrast, it is easy to show that EMPTY-CHILD (as well as LOSSY-CODE and BIJ-LOSSY-CODE) is not in PLS using Prover-Delayer games and resolution width lower bounds (see, e.g., [PT19, Proposition 3.4]).

**Remark 5.5.** Consider the following seemingly harder variant of EMPTY-CHILD-W-HEIGHT where the definition of **(Wrong Height)** is changed to

s4'. a vertex  $u \in V \setminus \{1\}$  such that  $\underline{H(u) \leq H(F(u))}$ . **(Wrong Height')**

Call this variant EMPTY-CHILD-W-HEIGHT'. We can define BINARY-EMPTY-CHILD-W-HEIGHT' likewise. Clearly, the proof of [Lemma 5.4](#) also shows that EMPTY-CHILD-W-HEIGHT' is in PLS (hence SOPL). Since EMPTY-CHILD-W-HEIGHT is LOSSY  $\cap$  SOPL-complete (as we will show in [Theorem 5.6](#)), it follows that EMPTY-CHILD-W-HEIGHT' is equivalent to EMPTY-CHILD-W-HEIGHT.

The difference between **(Wrong Height)** and **(Wrong Height')** resembles the difference between SINK-OF-METERED-LINE and SINK-OF-POTENTIAL-LINE. Indeed, our proof below (that EMPTY-CHILD-W-HEIGHT' reduces to EMPTY-CHILD-W-HEIGHT) starts from the fact that SINK-OF-METERED-LINE is SOPL-complete, hence it makes black-box use of the reduction from SINK-OF-POTENTIAL-LINE to SINK-OF-METERED-LINE [FGMS20].<sup>11</sup>

<sup>11</sup>Although [FGMS20] only claims a reduction from END-OF-POTENTIAL-LINE to END-OF-METERED-LINE, the same reduction also proves that SINK-OF-POTENTIAL-LINE reduces to SINK-OF-METERED-LINE.

Next, we show that **EMPTY-CHILD-W-HEIGHT** is complete for the class  $\text{LOSSY} \cap \text{SOPL}$ . The proof is inspired by the recent intersection results in **TFNP**:  $\text{CLS} = \text{PPAD} \cap \text{PLS}$  [FGHS23],  $\text{EOPL} = \text{PPAD} \cap \text{PLS}$ , and  $\text{SOPL} = \text{PPADS} \cap \text{PLS}$  [GHJ<sup>+</sup>24]. Given a **PPAD** instance  $A$  and a **PLS** instance  $B$ , [FGHS23] showed how to “combine”  $A$  and  $B$  into a **CLS** instance  $C$  such that a solution of  $C$  implies either a solution of  $A$  or a solution of  $B$ . Our idea is similar here: Given a **LOSSY-CODE** instance  $(f, g)$  and a **SINK-OF-METERED-LINE** instance  $(S, P, V)$ , we show how to create an instance  $(F, L, R, H)$  of **EMPTY-CHILD-W-HEIGHT** such that a solution of  $(F, L, R, H)$  implies either a solution of  $(f, g)$  or a solution of  $(S, P, V)$ . Roughly speaking, we use  $(f, g)$  to implicitly define an exponentially large tree and use  $(S, P, V)$  to define the heights on the tree.

**SINK-OF-METERED-LINE** [HY20, FGMS20]. Given functions  $S, P : [N] \rightarrow [N]$  and  $V : [N] \rightarrow [N] \cup \{0\}$  there are four types of possible solutions:

- s1.** 1, if  $P(1) \neq 1$  or  $S(1) = 1$  or  $V(1) \neq 1$ , (Bad Source)
- s2.** A vertex  $x \in [N]$  such that  $P(S(x)) \neq x$ , (Sink of Line)
- s3.** A vertex  $x \in [N] \setminus \{1\}$  such that  $V(x) = 1$ , (Bad Meter I)
- s4.** A vertex  $x \in [N]$  such that  $(V(x) > 0 \text{ and } V(S(x)) - V(x) \neq 1)$  or  $(V(x) > 1 \text{ and } V(x) - V(P(x)) \neq 1)$ . (Bad Meter II)

**Theorem 5.6.**  $\text{LOSSY-CODE} \cap \text{SINK-OF-METERED-LINE}$  reduces to **EMPTY-CHILD-W-HEIGHT** by a black-box reduction.

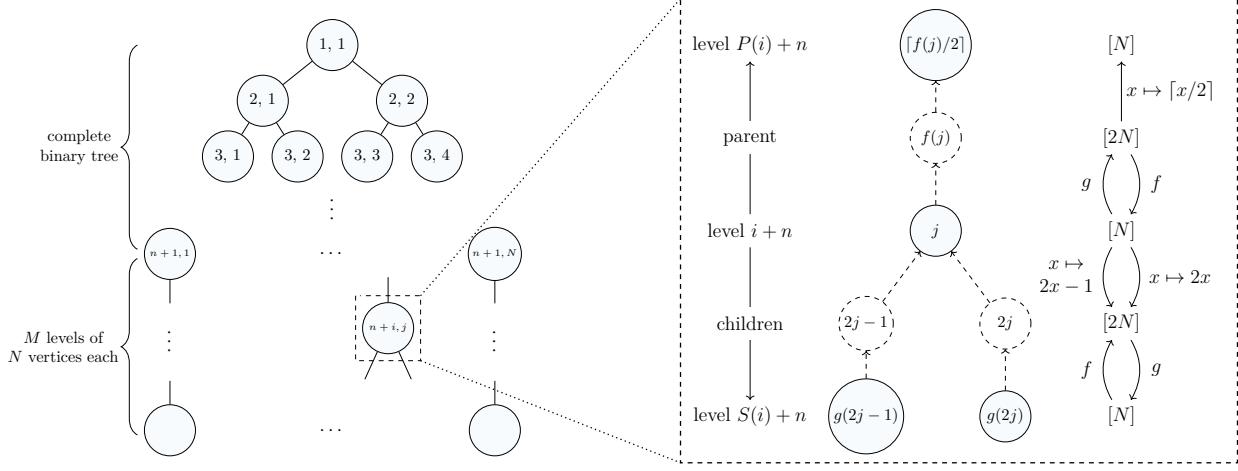
*Proof.* An input of  $\text{LOSSY-CODE} \cap \text{SINK-OF-METERED-LINE}$  consists of an instance  $(f, g)$  of **LOSSY-CODE** and an instance  $(S, P, V)$  of **SINK-OF-METERED-LINE**; either a solution for  $(f, g)$  or a solution for  $(S, P, V)$  is a valid solution. Now we show how to reduce this instance  $(f, g, S, P, V)$  to an instance of **EMPTY-CHILD-W-HEIGHT**. Let  $N, M$  denote the dimensions of the inputs, where  $f : [N] \rightarrow [2N]$ ,  $g : [2N] \rightarrow [N]$ ,  $S, P : [M] \rightarrow [M]$ , and  $V : [M] \rightarrow [M] \cup \{0\}$ . Without loss of generality, we may assume that  $N = 2^n$  is a power of 2 (this follows from the robustness of **LOSSY-CODE** as shown in [Lemma 2.3](#)).

We will create a “binary tree” with  $n + M$  levels. Roughly speaking, the first  $n$  levels form a complete binary tree, and each of the last  $M$  levels contains  $N$  vertices. Let  $(i, j)$  denote the  $j$ -th vertex in the  $i$ -th level; we abuse notation and write  $(i, j)$  also as the *index* of the node  $(i, j)$ , hence

$$(i, j) = \begin{cases} j + 2^{i-1} - 1 & \text{if } i \leq n, \\ j + N \cdot (i - n) - 1 & \text{otherwise.} \end{cases}$$

We now specify the structure of the tree.

- The father of the root is  $F(1, 1) := (1, 1)$ .
- For every  $2 \leq i \leq n + 1$  and  $j \in [2^{i-1}]$ ,  $F(i, j) := (i - 1, \lceil j/2 \rceil)$ .
- For every  $2 \leq i \leq M$  and  $j \in [N]$  s.t.  $V(i) \neq 0$ ,  $F(i + n, j) := (P(i) + n, \lceil f(j)/2 \rceil)$ .
- For every  $2 \leq i \leq M$  and  $j \in [N]$  s.t.  $V(i) = 0$ ,  $F(i + n, j) := (i + n, j)$ .
- For every  $i \in [n]$  and  $j \in [2^{i-1}]$ , the left and right children of  $(i, j)$  are  $L(i, j) := (i + 1, 2j - 1)$  and  $R(i, j) := (i + 1, 2j)$  respectively.
- For every  $i \in [M]$  and  $j \in [N]$  s.t.  $V(i) \neq 0$ ,  $L(i + n, j) := (S(i) + n, g(2j - 1))$  and  $R(i + n, j) := (S(i) + n, g(2j))$ .
- For every  $i \in [M]$  and  $j \in [N]$  s.t.  $V(i) = 0$ ,  $L(i + n, j) := R(i + n, j) := (i + n, j)$ .



**Figure 6:** The “tree” constructed in [Theorem 5.6](#). **Left:** The first  $n + 1$  levels form a complete binary tree and the last  $M$  levels are computed from the LOSSY-CODE instance  $(f, g)$  and the SINK-OF-METERED-LINE instance  $(S, P, V)$ . **Right:** For each node  $(i + n, j)$  in the last  $M$  levels, the levels of its parent and children are computed from  $(S, P)$ , and the positions of these nodes within their levels are computed from  $(f, g)$ .

- For every  $i \in [n]$ , the height of every node in the  $i$ ’th level is  $i$ .
- For every  $i \in [M]$ , the height of every node in the  $(i + n)$ ’th level is  $V(i) + n$ .

Now, given any solution  $(i', j)$  of EMPTY-CHILD-W-HEIGHT, we show how to obtain a solution of either  $(f, g)$  (for LOSSY-CODE) or  $(S, P, V)$  (for SINK-OF-METERED-LINE). In fact, from the above definitions of  $F, L, R$  one can see that it must be the case that  $i' > n$ ; moreover, if  $(i', j)$  has (**Wrong Height**), then it must be the case that  $i' > n + 1$  (unless  $V(1) = 1$  and 1 is a (**Bad Source**) for SINK-OF-METERED-LINE). Now we define  $i := i' - n$ , hence  $i \in [M]$ . We can see that

$$\begin{aligned} F(L(i', j)) &= (P(S(i)) + n, \lceil f(g(2j - 1))/2 \rceil); & (\text{if } S(i) \neq 1) \\ F(R(i', j)) &= (P(S(i)) + n, \lceil f(g(2j))/2 \rceil); & (\text{if } S(i) \neq 1) \\ H(i', j) - H(F(i', j)) &= V(i) - V(P(i)). & (\text{if } i > 1) \end{aligned}$$

Consider the following case analysis.

- Suppose that  $(i', j)$  has an (**Empty Child**). Clearly,  $V(i) \neq 0$ . If  $F(L(i', j)) \neq (i', j)$ , then either  $S(i) = 1$ , or  $P(S(i)) \neq i$ , or  $\lceil f(g(2j - 1))/2 \rceil \neq j$ . If  $F(R(i', j)) \neq (i', j)$ , then either  $S(i) = 1$ , or  $P(S(i)) \neq i$ , or  $\lceil f(g(2j))/2 \rceil \neq j$ . If  $L(i', j) = R(i', j) \neq (i', j)$ , then  $g(2j - 1) = g(2j)$ . Hence, one of the following holds:
  - $S(i) = 1$ . If  $P(1) \neq 1$  or  $S(1) = 1$ , then 1 is a (**Bad Source**) for SINK-OF-METERED-LINE; otherwise, since  $P(S(i)) = 1 \neq i$ ,  $i$  is a (**Sink of Line**) for SINK-OF-METERED-LINE.
  - $P(S(i)) \neq i$ . In this case,  $i$  is a (**Sink of Line**) for SINK-OF-METERED-LINE.
  - $\lceil f(g(2j - 1))/2 \rceil \neq j$ . In this case,  $f(g(2j - 1)) \neq 2j - 1$ , hence  $2j - 1$  is an answer for LOSSY-CODE.
  - $\lceil f(g(2j))/2 \rceil \neq j$ . In this case,  $f(g(2j)) \neq 2j$ , hence  $2j$  is an answer for LOSSY-CODE.
  - $g(2j - 1) = g(2j)$ . In this case, either  $f(g(2j - 1)) \neq 2j - 1$  or  $f(g(2j)) \neq 2j$ , hence we can find an answer for LOSSY-CODE.
- Clearly  $(1, 1)$  is not a (**Wrong Root**), so we do not need to care about this case.

- Suppose that  $(i', j)$  has **(Wrong Height)**. Then  $V(i) - V(P(i)) \neq 1$  and  $F(i', j) \neq (i', j)$ , which implies that  $V(i) \geq 1$ . If  $V(i) > 1$ , then  $i$  is a **(Bad Meter II)** for SINK-OF-METERED-LINE; otherwise  $i$  is a **(Bad Meter I)** for SINK-OF-METERED-LINE.

It follows that given a solution for relaxed EMPTY-CHILD-W-HEIGHT, we could find a solution for either LOSSY-CODE or SINK-OF-METERED-LINE.  $\square$

Since EMPTY-CHILD-W-HEIGHT is hard for LOSSY-CODE  $\cap$  SINK-OF-METERED-LINE (Theorem 5.6), is in SOPL (Lemma 5.4), and is in LOSSY (Lemma 5.3), we have:

**Corollary 5.7.** EMPTY-CHILD-W-HEIGHT is complete for  $\text{SOPL} \cap \text{LOSSY}$ .

Similarly, we can also reduce BIJ-LOSSY-CODE  $\cap$  END-OF-METERED-LINE to BINARY-EMPTY-CHILD-W-HEIGHT. Recall that END-OF-METERED-LINE is defined as follows:

**END-OF-METERED-LINE.** The input is functions  $S, P : [N] \rightarrow [N]$  and  $V : [N] \rightarrow [N] \cup \{0\}$  (i.e., same as SINK-OF-METERED-LINE). Besides the solutions of SINK-OF-METERED-LINE, we also accept the following solutions:

- s5.** A vertex  $x \in [N] \setminus \{1\}$  such that  $S(P(x)) \neq x$ . (End of Line)
- s6.** A vertex  $x \in [N]$  such that  $(V(x) > 0 \text{ and } V(S(x)) - V(x) \neq 1)$ . (Bad Meter III)

**Corollary 5.8.** BIJ-LOSSY-CODE  $\cap$  END-OF-METERED-LINE can be reduced to BINARY-EMPTY-CHILD-W-HEIGHT.

*Proof Sketch.* The reduction is exactly the same, except that we also need to handle the case that  $(i', j)$  has a **(Wrong Father)**. We can also see that  $i' > n + 1$ , hence  $i = i' - n \geq 2$ . We also have that  $V(i) \neq 0$ . Hence,

$$\begin{aligned} L(F(i', j)) &= (S(P(i)) + n, g(2\lceil f(j)/2 \rceil - 1)); & (\text{since } i > 1) \\ R(F(i', j)) &= (S(P(i)) + n, g(2\lceil f(j)/2 \rceil)). & (\text{since } i > 1) \end{aligned}$$

Hence, the case when  $(i', j)$  has a **(Wrong Father)** is argued as follows.

- Suppose that  $(i', j)$  has a **(Wrong Father)**. Letting  $v := 2\lceil f(j)/2 \rceil$ , then

$$(i', j) \notin \{(S(P(i)) + n, g(v - 1)), (S(P(i)) + n, g(v))\}.$$

Hence, one of the following holds:

- $i \neq S(P(i))$ . In this case,  $i$  is an **(End of Line)** for END-OF-METERED-LINE.
- $j \notin \{g(v - 1), g(v)\}$ . However  $f(j) \in \{v - 1, v\}$ , hence  $g(f(j)) \neq j$  and  $j$  is an answer for BIJ-LOSSY-CODE.  $\square$

### 5.3 LOSSY-Completeness of EMPTY-CHILD

Next, we adapt the above proof to show that LOSSY-CODE reduces to EMPTY-CHILD, establishing the equivalence between the two problems. Roughly speaking, our reduction makes use of two ideas:

1. LOSSY-CODE reduces to PPADS. In fact, a LOSSY-CODE instance  $f : [N] \rightarrow [2N]$  and  $g : [2N] \rightarrow [N]$  can be seen as a SINK-OF-LINE instance where  $g$  is the successor function,  $f$  is the predecessor function, and there are  $N$  distinguished sources numbered from  $N + 1$  to  $2N$ .

2. One can reduce LOSSY-CODE  $\cap$  PPADS to EMPTY-CHILD by slightly adapting the reduction in [Section 5.2](#), using the PPADS instance to handle the “heights”.

Our reduction starts by constructing a forest with  $2N$  levels, where each level contains  $N$  vertices. The children and parents of each vertex can then be defined in the same way as those in the bottom  $M$  levels of the tree from [Theorem 5.6](#), except that a vertex at the  $i$ -th level has its father at the  $f(i)$ -th level and children at the  $g(i)$ -th level. This is already a “forest” where every vertex in levels  $N + 1 \sim 2N$  are distinguished roots (hence there are  $N^2$  distinguished roots). Finally, we create a complete binary tree of depth  $\log(N^2)$  at the top to connect them.

**Theorem 5.9.** There is a reduction from LOSSY-CODE to EMPTY-CHILD.

*Proof.* Given  $f : [N] \rightarrow [2N]$  and  $g : [2N] \rightarrow [N]$  as the inputs to LOSSY-CODE, we construct an instance  $(F, L, R)$  of EMPTY-CHILD as follows: As in the proof of [Theorem 5.6](#), we may assume without loss of generality that  $N = 2^n$  is a power of 2. The “binary tree” has  $2(n + N)$  levels: the first  $2n$  levels form a perfect binary tree, while each of the remaining  $2N$  levels contains exactly  $N$  vertices. Following the notation in the proof of [Theorem 5.6](#), we write  $(i, j)$  for the  $j$ -th vertex in the  $i$ -th level. Slightly abusing notation, we also use  $(i, j)$  to denote the index of this vertex, namely

$$(i, j) = \begin{cases} j + 2^{i-1} - 1 & \text{if } i \leq 2n, \\ j + N \cdot (i - 2n - 1) + N^2 - 1 & \text{otherwise.} \end{cases}$$

The structure of the tree is described below:

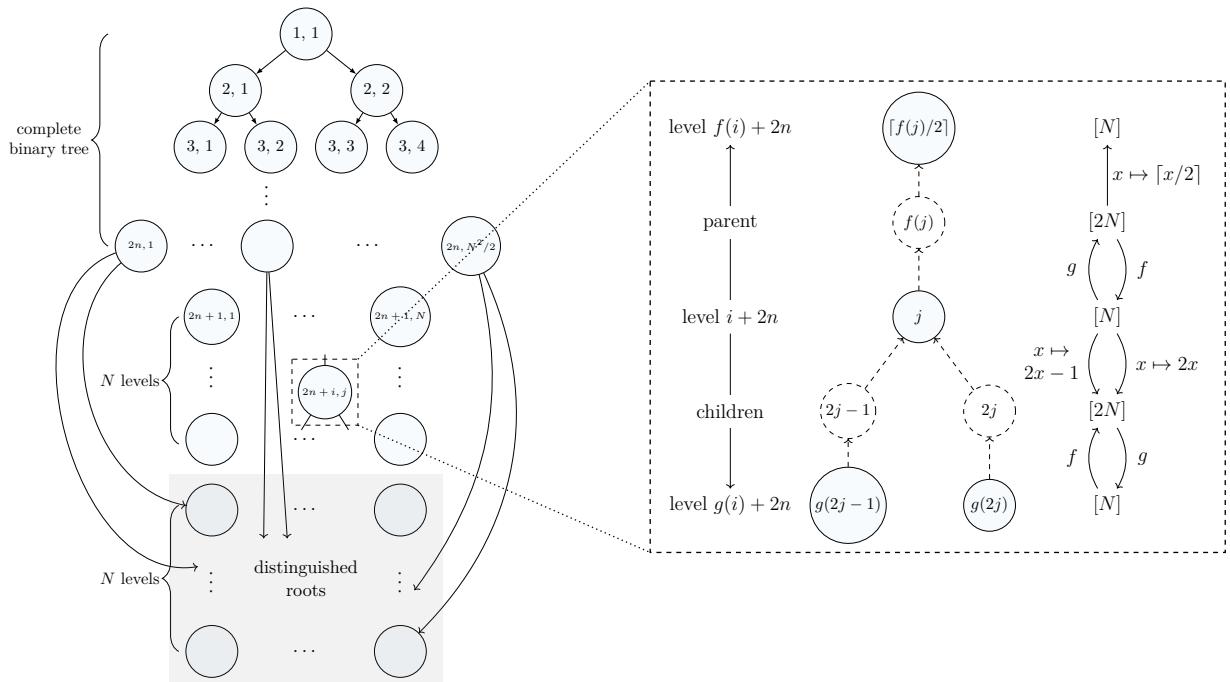
- The father of the root is  $F(1, 1) := (1, 1)$ .
- For every  $2 \leq i \leq 2n$  and  $j \in [2^{i-1}]$ ,  $F(i, j) := (i - 1, \lceil j/2 \rceil)$ .
- For every  $1 \leq i \leq N$  and  $j \in [N]$ ,  $F(i + 2n + N, j) := (2n, \lceil ((i - 1) \cdot N + j)/2 \rceil)$ .
- For every  $1 \leq i \leq N$  and  $j \in [N]$ ,  $F(i + 2n, j) := (f(i) + 2n, \lceil f(j)/2 \rceil)$ .
- For every  $i \in [2n-1]$  and  $j \in [2^{i-1}]$ , the left and right children of  $(i, j)$  are  $L(i, j) := (i + 1, 2j - 1)$  and  $R(i, j) := (i + 1, 2j)$  respectively.
- For every  $1 \leq i \leq N$  and  $j \in [N/2]$ ,  $L(2n, (i - 1)N/2 + j) := (i + 2n + N, 2j - 1)$  and  $R(2n, (i - 1)N/2 + j) := (i + 2n + N, 2j)$ .
- For every  $i \in [2N]$  and  $j \in [N]$ ,  $L(i + 2n, j) := (g(i) + 2n, g(2j - 1))$  and  $R(i + 2n, j) := (g(i) + 2n, g(2j))$ .

Given any solution  $(i', j)$  of EMPTY-CHILD, we show how to obtain a solution of LOSSY-CODE. Note that our EMPTY-CHILD instance only has solutions with **(Empty Child)**: **(Wrong Father)** and **(Wrong Height)** are not allowed, and **(Wrong Root)** does not apply since our tree has a “correct” root. Hence, we have that  $F(L(i', j)) \neq (i', j)$ , or  $F(R(i', j)) \neq (i', j)$ , or  $L(i', j) = R(i', j) \neq (i', j)$ . It follows from the structure of our tree that  $i' > 2n$ ; define  $i := i' - 2n$ . We have

$$\begin{aligned} F(L(i', j)) &= F(g(i) + 2n, g(2j - 1)) = (f(g(i)) + 2n, \lceil f(g(2j - 1))/2 \rceil); \\ F(R(i', j)) &= F(g(i) + 2n, g(2j)) = (f(g(i)) + 2n, \lceil f(g(2j))/2 \rceil). \end{aligned}$$

There are three cases:

- **Case I:**  $F(L(i', j)) \neq (i', j)$ . Then either  $f(g(i)) \neq i$ , or  $\lceil f(g(2j - 1))/2 \rceil \neq j$ . It follows that either  $i$  or  $2j - 1$  is a valid solution for LOSSY-CODE.



**Figure 7:** The “tree” constructed in [Theorem 5.9](#) where solid arrows represent tree edges. The first  $2n$  levels along with the last  $N$  levels form the perfect binary tree. Every vertex in the last  $N$  levels are distinguished roots of the bottom forest, and hence are the leaves of the perfect binary tree. The last  $2N$  levels form the bottom forest, whose structure is computed from the LOSSY-CODE instance  $(f, g)$ .

- **Case II:**  $F(R(i', j)) \neq (i', j)$ . Then either  $f(g(i)) \neq i$ , or  $\lceil f(g(2j))/2 \rceil \neq j$ . It follows that either  $i$  or  $2j$  is a valid solution for LOSSY-CODE.
- **Case III:**  $L(i', j) = R(i', j)$ . Then  $g(2j - 1) = g(2j)$ , which means that either  $2j$  or  $2j - 1$  is a valid solution for LOSSY-CODE.  $\square$

Similarly, BIJ-LOSSY-CODE reduces to BINARY-EMPTY-CHILD:

**Corollary 5.10.** There is a reduction from BIJ-LOSSY-CODE to BINARY-EMPTY-CHILD.

*Proof Sketch.* The reduction is exactly the same as in [Theorem 5.9](#), except that we also need to handle the case that  $(i', j)$  has a (**Wrong Father**). Clearly,  $i = i' - 2n \in [N]$ . Letting  $v := 2\lceil f(j)/2 \rceil$ , we have

$$\begin{aligned} L(F(i', j)) &= L(f(i) + 2n, \lceil f(j)/2 \rceil) = (g(f(i)) + 2n, g(v - 1)); \\ R(F(i', j)) &= R(f(i) + 2n, \lceil f(j)/2 \rceil) = (g(f(i)) + 2n, g(v)). \end{aligned}$$

Since  $(i', j) \notin \{L(F(i', j)), R(F(i', j))\}$ , there are two cases:

- **Case I:**  $i' \neq g(f(i)) + 2n$ . This implies that  $g(f(i)) \neq i$ , hence  $i$  is a valid solution for BIJ-LOSSY-CODE.
- **Case II:**  $j \notin \{g(v - 1), g(v)\}$ . However  $f(j) \in \{v - 1, v\}$ , hence  $g(f(j)) \neq j$  and  $j$  is a valid solution for BIJ-LOSSY-CODE.  $\square$

It is unclear whether BINARY-EMPTY-CHILD is equivalent to BIJ-LOSSY-CODE. We are unable to reduce the former to the latter, and the proof strategy of [Lemma 5.3](#) does not work here. We conjecture that (in the black-box setting) BINARY-EMPTY-CHILD is strictly harder than BIJ-LOSSY-CODE.

## 5.4 EMPTY-CHILD Reduces to NEPHEW

Recall once more the definition of NEPHEW:

**NEPHEW.** Given a set  $V$  of vertices and two functions  $f : V \rightarrow V$  and  $g : V \rightarrow V$ . Think of  $f(v)$  as the *father* of  $v$  and  $g(v)$  as the *nephew* of  $v$ . A solution is one of the following.

- s1.  $v \in V$  such that  $f(f(g(v))) \neq f(v)$  (your nephew's grandparent is not your parent)
- s2.  $v \in V$  such that  $f(g(v)) = v$  (you are your nephew's parent)

NEPHEW is at least as powerful as EMPTY-CHILD. We show a reduction from an EMPTY-CHILD instance  $(V, F, L, R)$  to a NEPHEW instance  $(V', f, g)$ , where  $V' = V \times \{0, 1\}$ . If there is an EMPTY-CHILD solution at  $v \in V$ , then both of  $(v, 0), (v, 1)$  will be self-loops for both  $f$  and  $g$ , giving a solution in the NEPHEW instance. Otherwise, we will construct a valid NEPHEW substructure. Special care will need to be taken in the case of isolated vertices in the EMPTY-CHILD instance, as well as for the distinguished root vertex  $1 \in V$ .

The procedure `Reduce-EC-to-Nephew` in [Algorithm 2](#) is the reduction. It takes in a vertex  $(v, i) \in V'$  and returns a tuple containing  $f(v, i)$  and  $g(v, i)$ . See [Figure 8](#) for an illustration of the NEPHEW instance returned by this procedure.

Before we prove its validity, we provide some intuition for the reduction. In the NEPHEW instance, we construct a structure where, for each vertex  $v \in V$ , the vertices corresponding to  $F(v)$  are pointed to via the  $f$  function and the vertices corresponding to  $L(v), R(v)$  are pointed to via the  $g$  function. In order to do this, we need to double the number of vertices:  $(v, 0)$  will point via  $g$  to  $R(v)$  and be pointed at via  $f$  by  $L(v)$ ; and  $(v, 1)$  will point via  $g$  to  $L(v)$  and be pointed at via  $f$  by  $R(v)$ . Isolated vertices and the root vertex will be handled separately.

---

**Algorithm 2** Procedure  $\text{Reduce-EC-to-Nephew}_{F,L,R}(v, i)$ 


---

```

1: if  $F(L(v)) \neq v \vee F(R(v)) \neq v \vee L(v) = R(v) \neq v$  then            $\triangleright (\text{Empty Child})$ , so self-loop
2:   return  $((v, i), (v, i))$ 
3: else if  $v = 1$  and  $L(1) = 1 \vee R(1) = 1 \vee F(1) \neq 1$  then            $\triangleright (\text{Wrong Root})$ , so self-loop
4:   return  $((1, i), (1, i))$ 
5: else if  $F(v) = L(v) = R(v) = v$  then            $\triangleright \text{Isolated vertex, treat specially}$ 
6:   return  $((1, 0), (v, 1 - i))$ 
7: else
8:   if  $v = 1$  then
9:      $f \leftarrow (1, 0)$ 
10:   else if  $v = R(F(v))$  then
11:      $f \leftarrow (F(v), 1)$ 
12:   else            $\triangleright v \neq 1 \text{ and } v \text{ is not a right child}$ 
13:      $f \leftarrow (F(v), 0)$ 
14:     if  $(v, i) = (1, 0)$  then
15:        $g \leftarrow (L(L(v)), 0)$ 
16:     else if  $(v, i) = (1, 1)$  then
17:        $g \leftarrow (1, 1)$ 
18:     else if  $i = 0$  then
19:        $g \leftarrow (R(v), 0)$ 
20:     else            $\triangleright v \neq 1 \text{ and } i = 1$ 
21:        $g \leftarrow (L(v), 0)$ 
22:   return  $(f, g)$ 

```

---

**Theorem 5.11.**  $(f(v, i), g(v, i)) \leftarrow \text{Reduce-EC-to-Nephew}_{F,L,R}$  is a reduction from EMPTY-CHILD to NEPHEW.

*Proof.* Consider any  $(v, i) \in V'$  such that  $v$  is a solution to EMPTY-CHILD. Then there is a self-loop on  $(v, i)$  with both  $f$  and  $g$ , meaning that  $f(g(v, i)) = (v, i)$ , and so  $(v, i)$  is a solution to the NEPHEW instance. Given such an NEPHEW solution, then, it is easy to find a solution to EMPTY-CHILD by checking  $v$ . Additionally, it is possible for there to be a NEPHEW solution if an EMPTY-CHILD solution exists at  $L(v)$  or  $R(v)$ , or at  $v = 1$  if a solution exists at  $L(L(1))$ . Again, it is easy to check if any of these is the case.

We will show that those scenarios are the only solutions to the NEPHEW instance. Consider any  $(v, i) \in V'$  and assume there is no solution at  $v$ ,  $L(v)$ ,  $R(v)$ , or  $L(L(1))$ . Then we have the following cases:

- $F(v) = L(v) = R(v) = v$ . Note then  $v \neq 1$ .

There is no solution of type 1:

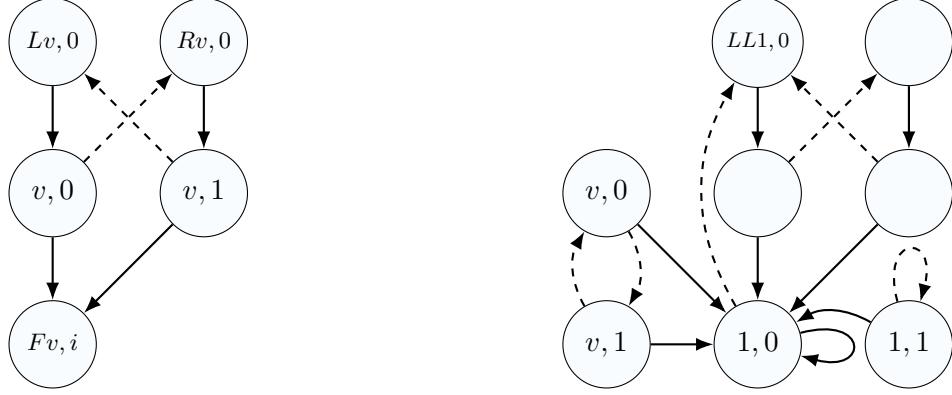
$$f(f(g(v, i))) = f(f(v, 1 - i)) = f(1, 0) = (1, 0) = f(v, i),$$

where the second-to-last equality comes from the fact that either 1 is not a solution, so  $f(1, 0) = (1, 0)$ , or 1 is a solution and  $(1, 0)$  self-loops.

There is no solution of type 2:

$$f(g(v, i)) = f(v, 1 - i) = (1, 0) \neq (v, i).$$

For the remaining cases, assume  $F(v) = L(v) = R(v) = v$  does not hold.



(a) Local NEPHEW structure for a typical node  $v$ . The value of  $i$  depends on whether or not  $v$  is a right child.

(b) Local NEPHEW structure around node 1, with a node  $v$  that is a self-loop in EMPTY-CHILD.

**Figure 8:** Illustration of Reduce-EC-to-Nephew $_{F,L,R}$ . Solid arrows represent  $f$  and dashed arrows represent  $g$ . Parentheses are omitted in labels.

- $(v, i) = (1, 0)$ .

There is no solution of type 1:

$$\begin{aligned} f(f(g(1, 0))) &= f(f(L(L(1)), 0)) = f(F(L(L(1))), 0) = f(L(1), 0) = (F(L(1)), 0) = (1, 0) \\ &= f(1, 0), \end{aligned}$$

where we used the fact that  $L(1)$  and  $L(L(1))$  are not solutions.

There is no solution of type 2:

$$f(g(1, 0)) = f(L(L(1)), 0) = (F(L(L(1))), 0) = (L(1), 0) \neq (1, 0).$$

- $(v, i) = (1, 1)$ .

There is no solution of type 1:

$$f(f(g(1, 1))) = f(f(1, 1)) = f(1, 0) = (1, 0) = f(1, 1).$$

There is no solution of type 2:

$$f(g(1, 1)) = f(1, 1) = (1, 0) \neq (1, 1).$$

- $v \neq 1$  and  $i = 0$ . Observe that  $R(F(R(v))) = R(v)$ , as  $F(R(v)) = v$ .

There is no solution of type 1:

$$f(f(g(v, 0))) = f(f(R(v), 0)) = f(F(R(v)), 1) = f(v, 1) = f(v, 0),$$

where the last inequality comes from the fact that  $(v, 0)$  and  $(v, 1)$  will always map to the same value under  $f$ .

There is no solution of type 2:

$$f(g(v)) = f(R(v), 0) = (F(R(v)), 1) = (v, 1) \neq (v, 0).$$

- $v \neq 1$  and  $i = 1$ .

There is no solution of type 1:

$$f(f(g(v, 1))) = f(f(L(v), 0)) = f(F(L(v)), 0) = f(v, 0) = f(v, 1),$$

where the last inequality comes from the fact that  $(v, 0)$  and  $(v, 1)$  will always map to the same value under  $f$ .

There is no solution of type 2:

$$f(g(v, i)) = f(L(v), 0) = (F(L(v)), 0) = (v, 0) \neq (v, 1).$$

We have ruled out NEPHEW solutions other than those listed before the case analysis. Thus, every solution in the NEPHEW instance can be used to efficiently map back to an EMPTY-CHILD solution as required.  $\square$

Combining [Theorem 5.11](#) with [Theorem 5.9](#), we obtain the following.

**Corollary 5.12.** There is a reduction from LOSSY-CODE to NEPHEW.

## 5.5 EMPTY-CHILD and NEPHEW with Inverse

It seems to be difficult to reduce NEPHEW to EMPTY-CHILD. It is possible that NEPHEW is strictly more powerful than EMPTY-CHILD. However, a proof of this seems elusive. To demonstrate this, we consider a natural modification to NEPHEW by adding an *inverse* to  $f$ . Interestingly, we show that this results in a problem that is *equivalent* to EMPTY-CHILD. If we believe that this modification is superficial, we could take this as evidence that NEPHEW and EMPTY-CHILD are in fact equivalent. Alternatively, it could indicate that any proof that shows that NEPHEW does not reduce to EMPTY-CHILD needs to argue how an inverse to  $f$  makes NEPHEW significantly easier.

We need to be a little bit careful in our definition of the inverse function. In the previous subsection we reduced EMPTY-CHILD to NEPHEW and created vertices that were not solutions yet were not pointed at via the  $f$  function: for an illustration see [Figure 8b](#). This situation only arises in the case where  $f(f(v)) = f(v)$ . Therefore we allow  $f^{-1}(v) = \perp$  in instances where  $f(f(v)) = f(v)$ .

**NEPHEW-W-INVERSE.** Given the same inputs as in NEPHEW and a function  $f^{-1} : V \rightarrow V \cup \{\perp\}$ , in addition to the solutions of NEPHEW, we accept the following solutions:

- s3.  $v \in V$  such that  $f^{-1}(v) \neq \perp$  and  $f(f^{-1}(v)) \neq v$ . (Wrong Inverse)
- s4.  $v \in V$  such that  $f^{-1}(v) = \perp$  and  $f(f(v)) \neq f(v)$ . (Bad  $\perp$ )

First we show that [Reduce-EC-to-Nephew](#) can be augmented to include the inverse function, and therefore EMPTY-CHILD reduces to NEPHEW-W-INVERSE. This augmented procedure is shown in [Algorithm 3](#). It returns a tuple  $(f, f^{-1}, g)$ . New additions are in blue and underlined.

**Theorem 5.13.** EMPTY-CHILD reduces to NEPHEW-W-INVERSE.

*Proof.* [Theorem 5.11](#) shows that [Reduce-EC-to-Nephew](#) is a reduction from EMPTY-CHILD to NEPHEW. The analysis in that proof still holds, as the  $f$  and  $g$  pointers returned are unmodified by the augmentation to [Reduce-EC-to-NwI](#). Thus, all that is left to do is to prove that no additional solutions are introduced by the addition of the  $f^{-1}$  pointer.

As in the proof of [Theorem 5.11](#), consider  $(v, i) \in V'$  and assume there is no solution at  $v, L(v), R(v)$ , or  $L(L(1))$ . We know already that there are no solutions of types 1 or 2. All that is left to prove is that no solutions of type 3 (**Wrong Inverse**) or type 4 (**Bad  $\perp$** ) exist.

- $F(v) = L(v) = R(v) = v$ . Note then  $v \neq 1$ .  $f^{-1}(v) = \perp$ , so we need only to consider solutions of type 4. None exist:

$$f(f(v, i)) = f((1, 0)) = (1, 0) = f(v, i).$$

---

**Algorithm 3** Procedure  $\text{Reduce-EC-to-NwI}_{F,L,R}(v, i)$ 


---

```

1: if  $F(L(v)) \neq v \vee F(R(v)) \neq v \vee L(v) = R(v) \neq v$  then
2:   return  $((v, i), (\underline{v}, \underline{i}), (v, i))$                                  $\triangleright (\text{Empty Child})$ , so self-loop
3: else if  $v = 1$  and  $L(1) = 1 \vee R(1) = 1 \vee F(1) \neq 1$  then
4:   return  $((1, i), (\underline{1}, \underline{i}), (1, i))$                                  $\triangleright (\text{Wrong Root})$ , so self-loop
5: else if  $F(v) = L(v) = R(v) = v$  then
6:   return  $((1, 0), \underline{\perp}, (v, 1 - i))$                                  $\triangleright \text{Isolated vertex, treat specially}$ 
7: else
8:   if  $v = 1$  then
9:      $f \leftarrow (1, 0)$ 
10:  else if  $v = R(F(v))$  then
11:     $f \leftarrow (F(v), 1)$ 
12:  else                                                                $\triangleright v \neq 1 \text{ and } v \text{ is not a right child}$ 
13:     $f \leftarrow (F(v), 0)$ 
14:    if  $(v, i) = (1, 0)$  then
15:       $g \leftarrow (L(L(v)), 0)$ 
16:       $\underline{f^{-1}} \leftarrow (\underline{L(v)}, 0)$ 
17:    else if  $(v, i) = (1, 1)$  then
18:       $g \leftarrow (1, 1)$ 
19:       $\underline{f^{-1}} \leftarrow \underline{\perp}$ 
20:    else if  $i = 0$  then
21:       $g \leftarrow (R(v), 0)$ 
22:       $\underline{f^{-1}} \leftarrow (\underline{L(v)}, 0)$ 
23:    else                                                                $\triangleright v \neq 1 \text{ and } i = 1$ 
24:       $g \leftarrow (L(v), 0)$ 
25:       $\underline{f^{-1}} \leftarrow (\underline{R(v)}, 0)$ 
26:  return  $(f, \underline{f^{-1}}, g)$ 

```

---

- $(v, i) = (1, 0)$ .  $f^{-1}(v) \neq \perp$ , so we need only to consider solutions of type 3. None exist:

$$f(f^{-1}(1, 0)) = f(L(1), 0) = (F(L(1)), 0) = (1, 0).$$

- $(v, i) = (1, 1)$ .  $f^{-1}(v) = \perp$ , so we need only to consider solutions of type 4. None exist:

$$f(f(1, 1)) = f(1, 0) = (1, 0) = f(1, 1).$$

- $v \neq 1$  and  $i = 0$ .  $f^{-1}(v) \neq \perp$ , so we need only to consider solutions of type 3. None exist:

$$f(f^{-1}(v, 0)) = f(L(v), 0) = (F(L(v)), 0) = (v, 0).$$

- $v \neq 1$  and  $i = 1$ .  $f^{-1}(v) \neq \perp$ , so we need only to consider solutions of type 3. None exist:

$$f(f^{-1}(v, 1)) = f(R(v), 0) = (F(R(v)), 1) = (v, 1).$$

□

We will now show that NEPHEW-W-INVERSE reduces to EMPTY-CHILD. To do so, we will reduce it to EMPTY-CHILD'.

**Theorem 5.14.** NEPHEW-W-INVERSE reduces to EMPTY-CHILD'.

---

**Algorithm 4** Procedure  $\text{Find-Children-and-Parent}_{f,f^{-1},g}(v)$ 


---

```

1: if  $f^{-1}(v) = \perp$  then
2:   return (v, v; v)                                 $\triangleright$  Self-loop on vertices with no f-inverse.
3: else
4:    $v' \leftarrow f^{-1}(v)$                           $\triangleright$  We will use the f-inverse of v as our starting point.
5:    $h(v') \leftarrow g(f(g(v')))$                     $\triangleright$  Rename for notational brevity
6:   if  $\text{CheckSol}(v) \vee \text{CheckSol}(v') \vee \text{CheckSol}(f(g(v')))$  then
7:     return ( $\perp, \perp; f(v)$ )                    $\triangleright$  We have found a solution, but always return f(v).
8:   else
9:     return ( $f(g(v')), f(h(v')); f(v)$ )  $\triangleright$  The two children of v are f(g(v')) and f(h(v')); the parent of v is f(v).

```

---

*Proof.* We use a variant of the **Find-Children** procedure named **Find-Children-and-Parent** that in addition also returns the parent vertex. Here, we define **CheckSol**(u) to be the procedure that returns **True** iff u is a solution to the NEPHEW-W-INVERSE instance.

**Find-Children-and-Parent** is given in [Algorithm 4](#). See [Figure 9](#) for an illustration. We show some useful properties of this procedure.

**Claim 5.15.** Let  $\text{Find-Children-and-Parent}_{f,f^{-1},g}(v) = (a, b; c)$ . Suppose  $f^{-1}(v) \neq \perp$ . If  $(a, b) \neq (\perp, \perp)$ , then

- (i)  $a \neq b$ ,
- (ii)  $f(a) = f(b) = v$ .

*Proof of [Claim 5.15](#).*

- (i) As  $a$  is not a solution, we know that  $b = f(g(a)) \neq a$ .
- (ii) As  $v$  is not a solution,  $f(v') = f(f^{-1}(v)) = v$ . As  $v'$  is not a solution,  $f(a) = f(f(g(v'))) = f(v') = v$ . As  $a$  is not a solution,  $f(b) = f(f(g(a))) = f(a) = v$ .  $\diamond$

Now we show the reduction. First, we need to choose a vertex from the NEPHEW-W-INVERSE instance to be our distinguished vertex 1 in **EMPTY-CHILD'**. We will select it such that  $f(f(1)) \neq f(1)$ .

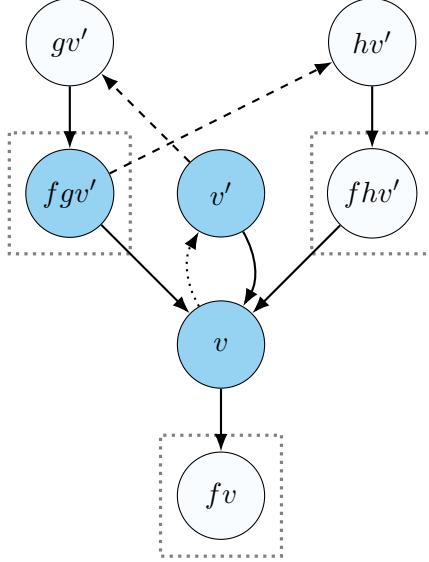
Let  $v^*$  be the lexicographically first NEPHEW-W-INVERSE vertex. Before performing the rest of the reduction, check the vertices  $\{v^*, f(v^*), g(f(v^*))\}$  to see if they are solutions. If any are, halt the reduction by returning some easily-falsified **EMPTY-CHILD'** instance (e.g. a single vertex that self-loops on  $F, L, R$ ). Given such an **EMPTY-CHILD'** instance we can easily find a solution to the NEPHEW-W-INVERSE instance by ensuring that our reduction always checks these specified vertices.

**Claim 5.16.** If none of  $\{v^*, f(v^*), g(f(v^*))\}$  are NEPHEW-W-INVERSE solutions, then either  $f(f(v^*)) \neq f(v^*)$  or  $f(f(g(f(v^*)))) \neq f(g(f(v^*)))$ .

*Proof.* Assume otherwise.  $f(v^*)$  is not a solution, so  $f(f(g(f(v^*)))) = f(f(v^*))$  and  $f(g(f(f(v^*)))) \neq f(v^*)$ . Then

$$f(f(v^*)) = f(f(g(f(f(v^*)))) = f(g(f(f(v^*)))) \neq f(v^*),$$

a contradiction.  $\diamond$



**Figure 9:** The procedure performed by  $\text{Find-Children-and-Parent}_{f,f^{-1},g}(v)$ . Solid arrows represent  $f$ , the dotted arrow represents  $f^{-1}$ , and dashed arrows represent  $g$ . Parentheses are omitted in labels. The dotted boxes indicate the vertices that will be returned. The procedure will check if the shaded vertices are NEPHEW-W-INVERSE solutions, and in doing so will visit the unshaded vertices (but will not detect if these are solutions). Note that  $f(h(v')) = v'$  is possible.

Set vertex 1 to be  $v^*$  if  $f(f(v^*)) \neq f(v^*)$  and  $g(f(v^*))$  otherwise. In the following, assume we have relabeled  $V$  such that the vertex chosen above is vertex 1.

For every vertex  $v$ , if  $\text{Find-Children-and-Parent}_{f,f^{-1},g}(v)$  returns  $(\perp, \perp, c)$ , let  $v^*$  be any vertex other than  $v$ , and assign  $L(v) = v^*$ ,  $R(v) = v^*$ , and  $F(v) = c$ . This will be an EMPTY-CHILD' solution of type **(Empty Child)** and we can easily compute an NEPHEW-W-INVERSE solution if such an EMPTY-CHILD' solution is detected: check  $v$ ,  $v'$ , and  $f(g(v'))$  for solutions. Otherwise, assign

$$(L(v), R(v); F(v)) \leftarrow \text{Find-Children-and-Parent}_{f,f^{-1},g}(v).$$

We will show that the only solutions to the EMPTY-CHILD' instance are those that are associated with  $(\perp, \perp, c)$  outputs as described above. Consider any  $v$  in the EMPTY-CHILD' instance and split into two cases: one where  $F(v) = L(v) = R(v) = v$  and one where this does not hold.

In the first case:

- $F(L(v)) = F(v) = v$  and  $F(R(v)) = F(v) = v$ .
- $L(v) = R(v) = v$ .
- It is not the case that  $v = 1$ . We must have  $f^{-1}(v) = \perp$  but we used [Claim 5.16](#) to choose vertex 1 such that  $f(f(1)) \neq f(1)$ . Together, these would imply that 1 is a solution of type **(Bad  $\perp$ )**, but we also chose 1 to not be a solution.

In the second case, we may assume there is no NEPHEW-W-INVERSE solution at  $v$ ,  $v'$ , and  $f(g(v'))$ . Then:

- $F(L(v)) = v$  and  $F(R(v)) = v$  by [Claim 5.15 Item \(ii\)](#). Note that this is why we need to always return a value for  $F$  in  $\text{Find-Children-and-Parent}$ : even if  $L(v)$  or  $R(v)$  are solutions, they will still correctly point back to  $v$ .
- $L(v) \neq R(v)$  by [Claim 5.15 Item \(i\)](#).

- $L(1) \neq 1$  and  $R(1) \neq 1$ . We assigned vertex 1 such that  $f(f(1)) \neq f(1)$ , which implies  $f(1) \neq 1$ . Thus,  $F(L(1)) = 1$  but  $F(1) \neq 1$ , implying  $L(1) \neq 1$  and the same argument works for  $R$ .  $\square$

## 6 The Strength of LOSSY-CODE

We start with the following candidate problem that, at the beginning of this research, was conjectured to be strictly harder than LOSSY-CODE.

**$c$ -AMGM-LC.** Let  $c > 1$  be a constant,  $V := [2N]$  and  $P := [c \cdot N^2]$ .

The input is a coloring function  $C : V \rightarrow \{0, 1\}$  and two mappings  $F : P \rightarrow V \times V$ ,  $G : V \times V \rightarrow P$ . Let  $H := C^{-1}(0) \times C^{-1}(1)$ . The goal is to find solutions of either type:

<b>s1.</b> a pigeon $x \in P$ such that $G(F(x)) \neq x$ ;	<b>(Wrong Encoding-Decoding)</b>
<b>s2.</b> a pigeon $x \in P$ such that $F(x) \notin H$ ;	<b>(Invalid Hole)</b>

The main result in this section is that  $c$ -AMGM-LC is, in fact, reducible to LOSSY-CODE. Moreover, our techniques allow us to reduce problems similar to (and sometimes more complicated than)  $c$ -AMGM-LC to LOSSY-CODE in a *systematic* way; we provide two additional examples later ( $c$ -Dual-AMGM-LC in [Section 6.2.2](#) and a problem capturing the Inclusion-Exclusion principle in [Section 6.2.3](#)).

Some of the results in this section are already known in the world of bounded arithmetic: they follow from the machineries underlying Jeřábek's theory of (additive) approximate counting  $\text{APC}_1 := \text{PV}_1 + \text{dPHP}(\text{PV})$  [[Jer07a](#)]. For example, it is not hard to formalize the AM-GM inequality in  $\text{APC}_1$  (more precisely, prove in  $\text{APC}_1$  that  $c$ -AMGM-LC is total); Wilkie's witnessing theorem ([[Tha02](#)], [[Jer04](#), Proposition 1.14]) implies that every  $\text{NP}$  search problem provably total in  $\text{APC}_1$  (including  $c$ -AMGM-LC) reduces to LOSSY-CODE.

One of the goals of this section is to introduce the ideas of  $\text{APC}_1$  to audiences who are less familiar with  $\text{APC}_1$  (or bounded arithmetic in general). In [Section 6.1](#), we introduce reconstructive pseudorandom generators with *feasible witnesses*, which is the central technique underlying [[Jer07a](#)]. This technique allows us to put a wide range of problems similar to  $c$ -AMGM-LC inside LOSSY-CODE.

### 6.1 Basics of $\text{APC}_1$

This subsection presents some background of  $\text{APC}_1$  [[Jer07a](#)] that is needed in our reductions. In [[Jer07a](#)], Jeřábek uses the *Nisan–Wigderson generator* [[NW94](#)] to approximate the size of feasible sets. Looking ahead, we will abstract the properties needed for the Nisan–Wigderson generator as *reconstructive PRGs* with “feasible witnesses” in some sense.

We first define the notion of *injection-surjection pairs*. Let  $A, B$  be two sets. We say that there is an *injection-surjection pair* certifying  $|A| \leq |B|$  if there are polynomial-time computable functions  $f : A \rightarrow B$  and  $g : B \rightarrow A$  such that for every  $x \in A$ ,  $g(f(x)) = x$ . This will be denoted by the following notation

$$A \xrightarrow[f]{g} B.$$

(Note that in the above notation, the injection-surjection pair is implicitly assuming that the left-hand side ( $A$ ) is smaller than the right-hand side ( $B$ ); hence  $A \rightleftharpoons B$  and  $B \rightleftharpoons A$  have very different meanings.)

Injection-surjection pairs are the basic primitive used in  $\text{APC}_1$  to compare the sizes of two sets; roughly speaking, this is because the underlying principle is the *retraction (weak) pigeonhole principle* (over polynomial-time functions; i.e., the totality of **LOSSY-CODE**).

For any sets  $A, B$  and two functions  $A \xrightarrow[g]{f} B$ , we say that an input  $x \in A$  *witnesses* that  $A \rightleftharpoons B$  is not an injection-surjection pair, if  $g(f(x)) \neq x$ . Otherwise (i.e.,  $g(f(x)) = x$ ), we say that  $x$  *maps to itself* via  $A \rightleftharpoons B$ . We also use  $X \dot{\cup} Y$  to denote the *disjoint union* of two sets  $X, Y$ .

**APC<sub>1</sub>-provably reconstructive pseudorandom generators.** Let  $N = 2^n, D = 2^d, M = 2^m$ , a function  $\text{PRG} : [N] \times [D] \rightarrow [M]$  is called a  $(k, \varepsilon)$ -reconstructive PRG if for every subset  $S \subseteq [M]$ , for all but at most  $K := 2^k$  values of  $f \in [N]$ , we have

$$\left| \frac{|S \cap \text{PRG}_f|}{D} - \frac{|S|}{M} \right| \leq \varepsilon, \quad (3)$$

where we write  $\text{PRG}_f = \{\text{PRG}(f, \text{seed}) : \text{seed} \in [D]\}$  for convenience. Furthermore, we want this generator to have “feasible witnesses” in the following sense:

**Definition 6.1.** Let  $G_<^{(-)}, H_<^{(-)}, G_>^{(-)}, H_>^{(-)}$  be polynomial-time oracle algorithms. We say that  $f \in [N]$  *provides an  $\varepsilon$ -additive approximation of  $|S|$  feasibly*, if letting  $\text{val} := |S \cap \text{PRG}_f| \cdot (M/D)$ , then we have the following two injection-surjection pairs:

$$[\text{val}] \times [D] \xrightarrow[G_<^{(f,-)}]{H_<^{(f,-)}} (S \dot{\cup} [\varepsilon M]) \times [D], \text{ and} \quad (4)$$

$$S \times [D] \xrightarrow[G_>^{(f,-)}]{H_>^{(f,-)}} ([\text{val}] \dot{\cup} [\varepsilon M]) \times [D]. \quad (5)$$

Roughly speaking, these injection-surjection pairs certify (3):  $(G_<, H_<)$  certifies  $\frac{|S \cap \text{PRG}_f|}{D} \leq \frac{|S|}{M} + \varepsilon$ , while  $(G_>, H_>)$  certifies  $\frac{|S|}{M} \leq \frac{|S \cap \text{PRG}_f|}{D} + \varepsilon$ .

Fix  $S \subseteq [M]$ , we want that all but  $K$  values  $f \in [N]$  provide an  $\varepsilon$ -additive approximation of  $|S|$  feasibly. In fact, we can construct a pair of *reconstruction algorithm* **Comp** and **Decomp**, which are deterministic oracle algorithms satisfying the following. Given any witness  $w$  that (4) or (5) is *not* an injection-surjection pair, **Comp** <sup>$S$</sup> ( $f, w$ ) compresses  $f$  into an element  $\tilde{f} \in [K]$  (i.e., compresses  $f$  into  $k$  bits), and **Decomp** <sup>$S$</sup> ( $\tilde{f}$ ) decompresses  $\tilde{f}$  back to  $f$ .

The following theorem asserts that some explicit generator (in fact, the Nisan–Wigderson generator [NW94]) has “feasible witnesses” in the above sense. It is implicit in [Jeř07a]; for completeness, we provide a proof in [Appendix C](#).

**Theorem 6.2.** Let  $n, m \in \mathbb{N}$ ,  $\varepsilon > 0$ , and  $\rho > 1$  be parameters. Let  $d := O\left(\frac{\log^2(nm/\varepsilon)}{\log \rho}\right)$  and  $k := d + (\rho + 1)(m - 1) + O(\log(m/\varepsilon))$ . Let  $N := 2^n$ ,  $M := 2^m$ ,  $K := 2^k$ , and  $D := 2^d$ .

Then there is a  $(k, \varepsilon)$ -reconstructive generator  $\text{PRG} : [N] \times [D] \rightarrow [M]$  with  $\text{poly}(\rho mn/\varepsilon)$ -time deterministic oracle algorithms  $G_<, H_<, G_>, H_>, \text{Comp}, \text{Decomp}$  such that the following holds. For every set  $S \subseteq [M]$ , every  $f \in [N]$ , and every input  $w$  witnessing that either (4) or (5) is not an injection-surjection pair (where  $\text{val} := |S \cap \text{PRG}_f| \cdot \frac{M}{D}$ ), we have **Comp** <sup>$S$</sup> ( $f, w$ )  $\in [K]$  and

$$\text{Decomp}^S(\text{Comp}^S(f, w)) = f.$$

In particular, the above theorem implies that if we take  $f$  to be “hard enough” (i.e.,  $f$  is not in the range of  $\text{Decomp}^S$ ) then  $f$  provides an  $\varepsilon$ -additive approximation of  $|S|$  feasibly, analogous to the classical theorem that we can use a hard truth table to derandomize BPP. This is reminiscent of the “compress-or-random” technique in catalytic computing [Pyn24, CLMP25, KMPS25, AM25]: Any string  $f$  is either “random”, which means it can be used for derandomization, or “compressible” and admits a short description.

## 6.2 Reductions to Lossy-Code

### 6.2.1 AMGM-LC

We first show that  $c$ -AMGM-LC is in LOSSY-CODE.

**Theorem 6.3.** For every constant  $c > 1$ , there is a decision tree reduction of  $\text{polylog}(N)$  query complexity from  $c$ -AMGM-LC to LOSSY-CODE.

*Proof.* Let  $\varepsilon := (c-1)/3$ ,  $\rho := \lceil \log N \rceil$ ,  $d := O(\log \log N)$ ,  $k := d + (\rho+1) \log |V| + O(\log(|V|/\varepsilon)) \leq O(\log^2 N)$ , and  $n' := 10\lceil \log N \rceil^2$ . Let  $D := 2^d$ ,  $K := 2^k$ , and  $N' := 2^{n'}$ . Let  $\text{PRG} : [N'] \times [D] \rightarrow V$  be defined in [Theorem 6.2](#).

Let  $f \in [N']$ ; for now, it would be convenient to assume that  $f$  successfully provides  $\varepsilon$ -approximations feasibly. Then we can estimate the size of  $C^{-1}(0)$  as  $v_0 := |C^{-1}(0) \cap \text{PRG}_f| \cdot (2N)/D$ ; the estimation of  $|C^{-1}(1)|$  is thus  $2N - v_0 = |C^{-1}(1) \cap \text{PRG}_f| \cdot (2N)/D$ . Furthermore, we can obtain injection-surjection pairs (that depend on  $f$ )

$$C^{-1}(0) \times [D] \rightleftharpoons [v_0 + 2\varepsilon N] \times [D] \text{ and} \quad (6)$$

$$C^{-1}(1) \times [D] \rightleftharpoons [2N - v_0 + 2\varepsilon N] \times [D]. \quad (7)$$

Since

$$|C^{-1}(0)| \cdot |C^{-1}(1)| \leq (v_0 + \varepsilon \cdot 2N) \cdot (2N - v_0 + \varepsilon \cdot 2N) \leq (1 + 2\varepsilon)N^2,$$

we obtain an injection-surjection pair

$$C^{-1}(0) \times C^{-1}(1) \times [D]^2 \rightleftharpoons [(1 + 2\varepsilon)N^2] \times [D]^2. \quad (8)$$

Combining this with  $(F, G)$ , the purported injection-surjection pair from  $P$  to  $H$ , we obtain an injection-surjection pair

$$P \times [D]^2 \rightleftharpoons [(1 + 2\varepsilon)N^2] \times [D]^2. \quad (9)$$

Since  $|P| = cN^2 > (1 + \Omega(1)) \cdot (1 + 2\varepsilon)N^2$ , this would be a contradiction to the retraction weak pigeonhole principle. Hence, by solving LOSSY-CODE we can find a witness that (9) is not an injection-surjection pair, which is also an answer of the original  $c$ -AMGM-LC instance.

We have shown that given some  $f$  that successfully provides  $\varepsilon$ -approximations, we can reduce  $c$ -AMGM-LC to LOSSY-CODE. But what if  $f$  does not provide such approximations? In this case,  $\text{Comp}$  allows us to compress such  $f$  into a  $k$ -bit string. In particular:

- For any input  $(x, y)$  witnessing that (6) is not an injection-surjection pair,  $\text{Comp}^{C^{-1}(0)}(f, x, y)$  returns some  $\tilde{f} \in [K]$  such that  $\text{Decomp}^{C^{-1}(0)}(\tilde{f}) = f$ .
- For any input  $(x, y)$  witnessing that (7) is not an injection-surjection pair,  $\text{Comp}^{C^{-1}(1)}(f, x, y)$  returns some  $\tilde{f} \in [K]$  such that  $\text{Decomp}^{C^{-1}(1)}(\tilde{f}) = f$ .

Now we are ready to formally present our reduction from AMGM-LC to LOSSY-CODE. Let  $X := [N'] \times P \times [D]^2$ ,  $Y_1 := [N'] \times [(1 + 2\varepsilon)N^2] \times [D]^2$ ,  $Y_2 := [2] \times [K] \times P \times [D]^2$ , and  $Y := Y_1 \dot{\cup} Y_2$ . Then

$$\begin{aligned} |Y| &= N'(1 + 2\varepsilon)N^2 \cdot D^2 + 2K \cdot cN^2 \cdot D^2 \\ &\leq N'(1 + 2.1\varepsilon)N^2 D^2 \\ &\leq (1 - \Omega(1))N' \cdot cN^2 \cdot D^2 = (1 - \Omega(1))|X|. \end{aligned}$$

We reduce the AMGM-LC instance to a LOSSY-CODE instance that consists of a pair of functions  $F^* : X \rightarrow Y$  and  $G^* : Y \rightarrow X$ .

- The function  $F^* : X \rightarrow Y$  takes as inputs  $f \in [N']$  and  $(p, u_1, u_2) \in P \times [D]^2$ . It considers the injection defined in (9) that corresponds to  $f$  and computes its output  $(q, v_1, v_2)$  on input  $(p, u_1, u_2)$ . Then it checks whether  $f$  is “good”: if  $f$  is “good” then it outputs  $(f, q, v_1, v_2) \in Y_1$ , otherwise it outputs some value in  $Y_2$  containing a compression of  $f$ .

More precisely, let  $(a, b) := F(p)$ , assume that  $a \in C^{-1}(0)$  and  $b \in C^{-1}(1)$ . To evaluate (9) on input  $(p, u_1, u_2)$ , we need to evaluate  $(a, u_1)$  on (6) and  $(b, u_2)$  on (7). If  $(a, u_1)$  witnesses that (6) is not an injection-surjection pair, then  $f$  is not “good”, and  $f$  can be compressed into  $\tilde{f} := \text{Comp}^{C^{-1}(0)}(f, a, u_1) \in [K]$ . We return  $(0, \tilde{f}, p, u_1, u_2) \in Y_2$  in this case. Similarly, if  $(b, u_2)$  witnesses (7) is not an injection-surjection pair, then we let  $\tilde{f} := \text{Comp}^{C^{-1}(1)}(f, b, u_2) \in [K]$  and return  $(1, \tilde{f}, p, u_1, u_2) \in Y_2$ . If none of the above happens, then  $f$  is “good” and we return  $(f, q, v_1, v_2) \in Y_1$ .

- The function  $G^* : Y \rightarrow X$  can be decomposed into functions  $G_1^* : Y_1 \rightarrow X$  and  $G_2^* : Y_2 \rightarrow X$ . In either case, we are given a “compressed” form of some  $(f, p, u_1, u_2) \in X$  and need to recover  $(f, p, u_1, u_2)$ .

For  $G_1^* : Y_1 \rightarrow X$ , the “compressed form” is  $(f, q, v_1, v_2) \in Y_1$ . This corresponds to the case that  $f$  is “good”. We consider the surjection defined in (9) corresponding to  $f$  and compute its output  $(p, u_1, u_2)$  given input  $(q, v_1, v_2)$ . Then we output  $(f, p, u_1, u_2) \in X$ .

For  $G_2^* : Y_2 \rightarrow X$ , the “compressed form” is  $(b, \tilde{f}, p, u_1, u_2) \in Y_2$ . This corresponds to the case that  $f$  is “not good”, and we can directly compute  $f := \text{Decomp}^{C^{-1}(b)}(\tilde{f})$ . Then we output  $(f, p, u_1, u_2) \in X$ .

To see the correctness of this reduction, consider any input  $(f, p, u_1, u_2)$  witnessing that  $X \xrightleftharpoons[G^*]{F^*} Y$  is not an injection-surjection pair. There are two cases:

- Suppose that  $F^*(f, p, u_1, u_2) = (f, q, v_1, v_2) \in Y_1$ . Letting  $(a, b) := H(p)$ , this means that  $(a, u_1)$  maps to itself via (6), and  $(b, u_2)$  maps to itself via (7). In other words,  $(a, b, u_1, u_2)$  maps to itself via (8). Hence, it has to be the case that  $P \xrightleftharpoons[G]{F} C^{-1}(0) \times C^{-1}(1)$  does not map  $p$  to itself, which means that  $p$  is a solution to AMGM-LC.
- The other case is that  $F^*(f, p, u_1, u_2) = (b, \tilde{f}, p, u_1, u_2) \in Y_2$ . We claim that this case would not have happened. Indeed, in this case,  $G_2^*$  always maps  $(b, \tilde{f}, p, u_1, u_2)$  back to  $(f, p, u_1, u_2)$ .

Finally, it is easy to see that both  $F^*$  and  $G^*$  run in deterministic polylog( $N$ ) time.  $\square$

### 6.2.2 Dual-AMGM-LC

Now we define the *dual* of the problem  $c$ -AMGM-LC, which expresses the AM-GM inequality in a different way:

**$c$ -Dual-AMGM-LC.** Let  $V = [2N], H = [c \cdot N^2]$ . The input consists of a coloring function  $C : V \rightarrow \{0, 1\}$  and two mappings  $F : H \rightarrow V \times V, G : V \times V \rightarrow H$ . Let

$$P := \{(u, v) : C(u) = C(v)\} = (C^{-1}(0) \times C^{-1}(0)) \cup (C^{-1}(1) \times C^{-1}(1)).$$

The goal is to find a pigeon  $x \in P$  such that  $F(G(x)) \neq x$ .

**Theorem 6.4.** For every constant  $0 < c < 2$ , there is a decision tree reduction of  $\text{polylog}(N)$  query complexity from  $c$ -Dual-AMGM-LC to LOSSY-CODE.

*Proof.* Let  $\varepsilon := (2 - c)/32$  and  $c' := c + 8\varepsilon(1 + \varepsilon)$ , then  $c' < 2$ . Let  $\rho := \lceil \log N \rceil, d := O(\log \log N)$ ,  $n' := 10 \lceil \log N \rceil^2$ , and  $k := d + (\rho + 1)(\log |V| - 1) + O(\log(|V|/\varepsilon)) \leq 2 \lceil \log N \rceil^2$ . Let  $D := 2^d = \text{polylog}(N), K := 2^k, N' := 2^{n'}$ . Consider the generator  $\text{PRG} : [N'] \times D \rightarrow V$  in [Theorem 6.2](#).

Let  $f \in [N']$ . Let  $v_0 := |C^{-1}(0) \cap \text{PRG}_f| \cdot (2N/D)$  and  $v_1 := 2N - v_0$  be the estimations of  $|C^{-1}(0)|$  and  $|C^{-1}(1)|$  provided by  $\text{PRG}_f$ , respectively. Then we obtain (purported) injection-surjection pairs

$$\begin{aligned} [v_0] \times [D] &\rightleftharpoons (C^{-1}(0) \dot{\cup} [2\varepsilon N]) \times [D] \text{ and} \\ [v_1] \times [D] &\rightleftharpoons (C^{-1}(1) \dot{\cup} [2\varepsilon N]) \times [D]. \end{aligned}$$

This implies an injection-surjection pair

$$\begin{aligned} [v_0^2 + v_1^2] \times [D]^2 &\xrightleftharpoons[G_f]{F_f} \left( (C^{-1}(0) \dot{\cup} [2\varepsilon N])^2 \dot{\cup} (C^{-1}(1) \dot{\cup} [2\varepsilon N])^2 \right) \times [D]^2 \\ &= \left( P \dot{\cup} (C^{-1}(0) \dot{\cup} C^{-1}(1)) \times [4\varepsilon N] \dot{\cup} [2(2\varepsilon N)^2] \right) \times [D]^2 \\ &= (P \dot{\cup} [8\varepsilon(1 + \varepsilon)N^2]) \times [D]^2. \end{aligned}$$

Composing this with our input  $P \xrightleftharpoons[G]{F} H$  and noting that  $H = [cN^2]$  and  $v_0^2 + v_1^2 \geq 2N^2$ , we obtain

$$[2N^2] \times [D]^2 \xrightleftharpoons[G_f \circ G]{F \circ F_f} [(c + 8\varepsilon(1 + \varepsilon))N^2] \times [D]^2 = [c'N^2] \times [D]^2.$$

(Note that we are abusing notation here in “ $G_f \circ G$ ” and “ $F \circ F_f$ ”; for example, we are extending the domain of  $G$  to  $H \dot{\cup} [8\varepsilon(1 + \varepsilon)N^2]$  so that  $G$  is the identity map on  $[8\varepsilon(1 + \varepsilon)N^2]$ .)

Since  $(c + 8\varepsilon(1 + \varepsilon)) < 2 - \Omega(1)$ ,  $(F \circ F_f, G \circ G_f)$  is a valid LOSSY-CODE instance. Solving this LOSSY-CODE instance gives us a witness that  $(F \circ F_f, G \circ G_f)$  is not an injection-surjection pair. This implies either a witness that  $(F, G)$  is not an injection-surjection pair (which is what we need), or a witness that  $(F_f, G_f)$  is not an injection-surjection pair (which will allow us to compress  $f$ ).

Now we formally define the complete reduction from  $c$ -Dual-AMGM-LC to LOSSY-CODE. Let  $X := [N'] \times [2N^2] \times [D]^2, Y_1 := [N'] \times [c'N^2] \times [D]^2, Y_2 := [K + O(1)] \times [2N^2] \times [D]^2$ , and  $Y := Y_1 \dot{\cup} Y_2$ . Note that

$$|Y| = |Y_1| + |Y_2| \leq (c' + o(1))N'N^2D^2 \leq (2 - \Omega(1))N'N^2D^2 \leq (1 - \Omega(1))|X|.$$

We reduce the  $c$ -Dual-AMGM-LC instance  $(C, F, G)$  to the LOSSY-CODE instance  $X \xrightleftharpoons[G^*]{F^*} Y$ , defined as follows.

- The function  $F^* : X \rightarrow Y$  takes as inputs  $f \in [N']$  and  $u \in [2N^2] \times [D]^2$ . It tests if  $u$  is a witness that  $(F_f, G_f)$  is not an injection-surjection pair. If this is the case, then it uses  $\text{Comp}$  to compress  $f$  into  $K + O(1)$  bits as  $\tilde{f}$ , and returns  $(\tilde{f}, u) \in Y_2$ . Otherwise it computes  $v := F(F_f(u)) \in [c'N^2] \times [D]^2$  and returns  $(f, v) \in Y_1$ .

- The function  $G^* : Y \rightarrow X$  takes either  $(f, v) \in Y_1$  or  $(\tilde{f}, u) \in Y_2$  as inputs. If the input is  $(f, v) \in Y_1$  where  $f \in [N']$  and  $v \in [c'N^2] \times [D]^2$ , then it computes  $u := G(G_f(v)) \in [2N^2] \times [D]^2$  and returns  $(f, u) \in X$ . If the input is  $(\tilde{f}, u) \in Y_2$  where  $\tilde{f} \in [K + O(1)]$  and  $u \in [2N^2] \times [D]^2$ , then it decompresses  $f \in [N']$  from  $\tilde{f}$  and returns  $(f, u) \in X$ .

Given any  $(f, u) \in X$  witnessing that  $(F^*, G^*)$  is not an injection-surjection pair, we have that  $F^*(f, u) \in Y_1$  and we can find a witness that  $(F, G)$  is not an injection-surjection pair in deterministic  $\text{polylog}(N)$  time. Finally,  $F^*, G^*$  can be computed in deterministic  $\text{polylog}(N)$  time as well.  $\square$

### 6.2.3 The Inclusion-Exclusion Principle

Finally, as a proof-of-concept, we consider the following more complicated total search problem capturing the *inclusion-exclusion principle* and show that it is in **LOSSY**. Given that Jeřábek already proved this principle in APC1 [Jeř07a, Proposition 2.19], it should come as no surprise that this problem is in **LOSSY**. Needless to say, our proof is just a translation of Jeřábek's proof into the language of black-box total search problems. We include this example as an additional demonstration of how to reduce more complicated problems to **LOSSY-CODE** via [Theorem 6.2](#).

Consider the following inequality expressing the inclusion-exclusion principle: Let  $S_1, S_2, \dots, S_\ell \subseteq [N]$  be sets,  $a_i := |S_i|$ ,  $a_{i,j} := |S_i \cap S_j|$ , and

$$\tilde{a} := \sum_{i=1}^{\ell} a_i - \sum_{1 \leq i < j \leq \ell} a_{i,j}, \quad (10)$$

then  $\left| \bigcup_{i \in [\ell]} S_i \right| \geq \tilde{a}$ .

Now we formalize the above inequality as a **TFZPP** problem **INCLUSION-EXCLUSION**.

**INCLUSION-EXCLUSION.** The input consists of:

- Parameters  $N, \ell \leq \text{polylog}(N)$ , and  $\varepsilon > 1/\text{polylog}(N)$ .
- A table  $T \subseteq [\ell] \times [N]$  where  $T_{i,j} = 1$  if and only if  $j \in S_i$ .
- Numbers  $0 \leq a_i \leq N$  for each  $i \in [\ell]$ , and  $0 \leq a_{i,j} \leq N$  for each  $1 \leq i < j \leq \ell$ , which are purported estimates for  $|S_i|$  and  $|S_i \cap S_j|$  respectively. Let  $\tilde{a}$  be defined as in (10) and assume  $\tilde{a} \geq \varepsilon N$ .
- Injection-surjection pairs  $f_i : [a_i] \rightarrow [N]$  and  $g_i : [N] \rightarrow [a_i]$ .
- Injection-surjection pairs  $f_{i,j} : [a_{i,j}] \rightarrow [N]$  and  $g_{i,j} : [N] \rightarrow [a_{i,j}]$ .
- Finally, an injection-surjection pair  $\tilde{f} : [\tilde{a} - \varepsilon N] \rightarrow [N]$  and  $\tilde{g} : [N] \rightarrow [\tilde{a} - \varepsilon N]$ .

The goal is to find any solution of the following types:

- s1.** some  $x \in [a_i]$  such that  $T_{i,f_i(x)} = 0$  or  $g_i(f_i(x)) \neq x$ ; (**Violation of**  $|S_i| \geq a_i$ )
- s2.** some  $x \in [N]$  such that  $(T_{i,x} = T_{j,x} = 1)$  but  $f_{i,j}(g_{i,j}(x)) \neq x$ ; or (**Violation of**  $|S_i \cap S_j| \leq a_{i,j}$ )
- s3.** some  $x \in [N]$  such that  $\tilde{f}(\tilde{g}(x)) \neq x$ , and there is some  $j \in [\ell]$  such that  $T_{j,x} = 1$ . (**Violation of**  $\left| \bigcup_{i \in [\ell]} S_i \right| \leq \tilde{a} - \varepsilon N$ )

**Theorem 6.5.** **INCLUSION-EXCLUSION** reduces to **LOSSY-CODE**.

*Proof.* Let  $\varepsilon' := \varepsilon/(10\ell^2)$ ,  $\rho := \lceil \log N \rceil$ ,  $d := O(\log \log N)$ ,  $k := d + (\rho + 1) \log N + O(\log(N/\varepsilon)) \leq 3\lceil \log N \rceil^2$ , and  $n' := \log(100\ell^4\varepsilon^{-1}) + k \leq 4\lceil \log N \rceil^2$ . Let  $D := 2^d$ ,  $K := 2^k$ , and  $N' := 2^{n'}$ . Note

that  $d' \geq O(\frac{\log^2(n' \cdot \log N / \varepsilon')}{\log \rho})$ , hence it is valid to apply [Theorem 6.2](#) to obtain  $\text{PRG} : [N'] \times [D] \rightarrow [N]$ . Recall that we define  $S_i := \{j \in [N] : T_{i,j} = 1\}$ . We also define  $S := \bigcup_{i \in [\ell]} S_i$ .

Let  $f \in [N']$ . We use  $f$  to estimate each  $|S_i|$ ,  $|S_i \cap S_j|$ , and  $|S|$  within additive error  $\varepsilon' \cdot N$ . Let  $v_i := |S_i \cap \text{PRG}_f| \cdot (N/D)$ ,  $v_{i,j} := |S_i \cap S_j \cap \text{PRG}_f| \cdot (N/D)$ , and  $v := |S \cap \text{PRG}_f| \cdot (N/D)$ , then we obtain (purported) injection-surjection pairs

$$S_i \times [D] \xrightarrow[\overleftarrow{G_i}]{F_i} ([v_i] \dot{\cup} [\varepsilon' N]) \times [D], \quad (11)$$

$$[v_{i,j}] \times [D] \xrightarrow[\overleftarrow{F_{i,j}}]{G_{i,j}} ((S_i \cap S_j) \dot{\cup} [\varepsilon' N]) \times [D], \quad (12)$$

$$[v] \times [D] \xrightarrow[\overleftarrow{F}]{G} (S \dot{\cup} [\varepsilon' N]) \times [D]. \quad (13)$$

If  $v_i + 2\varepsilon' N < a_i$ , then we can compose (11) with the injection-surjection pair  $(f_i, g_i)$  to obtain the **LOSSY-CODE** instance

$$[a_i] \times [D] \xrightarrow[\overleftarrow{g_i \times [D]}]{f_i \times [D]} S_i \times [D] \xrightarrow[\overleftarrow{G_i}]{F_i} [v_i + \varepsilon' N] \times [D]. \quad (14)$$

Here, we use the notation  $f_i \times [D]$  to denote the function mapping  $(x, y)$  to  $(f_i(x), y)$ , where  $x \in [a_i]$  and  $y \in [D]$ ;  $g_i \times [D]$  is defined similarly. Note that since  $\frac{(v_i + \varepsilon' N) \cdot D}{a_i \cdot D} \leq 1 - \frac{\varepsilon' N}{a_i} \leq \varepsilon'$ , (14) is a valid **LOSSY-CODE** instance with good stretch; in particular, it reduces to standard **LOSSY-CODE** (of stretch  $[2t] \Rightarrow [t]$ ) in decision tree depth  $O(1/\varepsilon')$ . Solving the instance (14) gives us an element  $(x, y) \in [a_i] \times [D]$  such that either (1)  $x$  is a **(Violation of  $|S_i| \geq a_i$ )** or (2)  $(f_i(x), y) \in S_i \times [D]$  witnesses that (11) is not a valid injection-surjection pair.

Similarly, if  $v_{i,j} > a_{i,j} + 2\varepsilon' N$ , then we compose (12) with the injection-surjection pair  $(f_{i,j}, g_{i,j})$  to obtain the **LOSSY-CODE** instance

$$[v_{i,j}] \times [D] \xrightarrow[\overleftarrow{F_{i,j}}]{G_{i,j}} ((S_i \cap S_j) \dot{\cup} [\varepsilon' N]) \times [D] \xrightarrow[\overleftarrow{f_{i,j} \times [D]}]{g_{i,j} \times [D]} [a_{i,j} + \varepsilon' N] \times [D]. \quad (15)$$

Again, we abuse notation to extend  $f_{i,j}$  and  $g_{i,j}$  into functions  $f_{i,j} : [a_{i,j}] \dot{\cup} [\varepsilon' N] \rightarrow [N] \dot{\cup} [\varepsilon' N]$  and  $g_{i,j} : [N] \dot{\cup} [\varepsilon' N] \rightarrow [a_{i,j}] \dot{\cup} [\varepsilon' N]$  such that they are the identity function over  $[\varepsilon' N]$ . (15) is a valid **LOSSY-CODE** instance that reduces to the standard **LOSSY-CODE** in decision tree depth  $O(1/\varepsilon')$ . Solving the instance (15) gives us an element  $(x, y) \in [v_{i,j}] \times [D]$  such that either (1)  $x' := G_{i,j}(x)$  is a **(Violation of  $|S_i \cap S_j| \leq a_{i,j}$ )** or (2)  $(x, y)$  witnesses that (12) is not a valid injection-surjection pair.

Finally, if  $v > \tilde{a} - \varepsilon N + 2\varepsilon' N$ , then we compose (13) with the injection-surjection pair  $(\tilde{f}, \tilde{g})$  to obtain the **LOSSY-CODE** instance

$$[v] \times [D] \xrightarrow[\overleftarrow{F}]{G} (S \dot{\cup} [\varepsilon' N]) \times [D] \xrightarrow[\overleftarrow{\tilde{f} \times [D]}]{\tilde{g} \times [D]} [\tilde{a} - \varepsilon N + \varepsilon' N] \times [D]. \quad (16)$$

Solving the instance (16) gives us an element  $(x, y) \in [v] \times [D]$  such that either (1)  $x' := G(x)$  is a **(Violation of  $|\bigcup_{i \in [\ell]} S_i| \leq \tilde{a} - \varepsilon N$ )** or (2)  $(x, y)$  witnesses that (13) is not a valid injection-surjection pair.

We now observe that one of the above three cases must happen. This is exactly due to the inclusion-exclusion principle itself: Let  $\tilde{S}_i := S_i \cap \text{PRG}_f$ , then

$$\left| \bigcup_{i \in [\ell]} \tilde{S}_i \right| \geq \sum_{i=1}^{\ell} |\tilde{S}_i| - \sum_{1 \leq i < j \leq \ell} |\tilde{S}_i \cap \tilde{S}_j|.$$

Recall that  $v_i = |\tilde{S}_i|(N/D)$ ,  $v_{i,j} = |\tilde{S}_i \cap \tilde{S}_j|(N/D)$ , and  $v = \left| \bigcup_{i \in [\ell]} \tilde{S}_i \right|(N/D)$ , hence  $v \geq \sum_{i=1}^{\ell} v_i - \sum_{1 \leq i < j \leq \ell} v_{i,j}$ . If all three cases above do not happen, then

$$\begin{aligned}
\tilde{a} &\geq v + \varepsilon N - 2\varepsilon' N & (\because v > \tilde{a} - \varepsilon N + 2\varepsilon' N \text{ does not happen}) \\
&\geq \sum_{i=1}^{\ell} v_i - \sum_{1 \leq i < j \leq \ell} v_{i,j} + \varepsilon N - 2\varepsilon' N \\
&\geq \sum_{i=1}^{\ell} (a_i - 2\varepsilon' N) - \sum_{1 \leq i < j \leq \ell} v_{i,j} + \varepsilon N - 2\varepsilon' N & (\because v_i + 2\varepsilon' N < a_i \text{ does not happen}) \\
&\geq \sum_{i=1}^{\ell} (a_i - 2\varepsilon' N) - \sum_{1 \leq i < j \leq \ell} (a_{i,j} + 2\varepsilon' N) + \varepsilon N - 2\varepsilon' N & (\because v_{i,j} > a_{i,j} + 2\varepsilon' N \text{ does not happen}) \\
&\geq \sum_{i=1}^{\ell} a_i - \sum_{1 \leq i < j \leq \ell} a_{i,j} + (\varepsilon - 5\ell^2\varepsilon')N > \tilde{a},
\end{aligned}$$

a contradiction.

Now we are ready to describe our reduction from INCLUSION-EXCLUSION to LOSSY-CODE. Let  $X := [N'] \times [2N] \times [D]$  and  $Y$  be some set that we will define later, we will produce a LOSSY-CODE instance  $X \xrightarrow[G^*]{F^*} Y$ . Given an element in  $X$ , we parse it as  $(f, x, y)$  where  $f \in [N']$ ,  $x \in [2N]$ , and  $y \in [D]$ . To compute  $F^*(f, x, y)$ , we find out which of the above three cases happens for  $f$ .

- **Case I:** Suppose that there exists  $i \in [\ell]$  such that  $v_i + 2\varepsilon' N < a_i$ . If  $x \notin [a_i]$ , then we let  $x' := x - \varepsilon' N$  and  $y' := y$ ; otherwise we feed  $(x, y)$  into

$$[a_i] \times [D] \xrightarrow[g_i \times [D]]{f_i \times [D]} S_i \times [D] \xrightarrow[G_i]{F_i} [v_i + \varepsilon' N] \times [D] \quad (14)$$

to obtain  $(x', y') \in [v_i + \varepsilon' N] \times [D]$ . We define  $Y_0 := [N'] \times [2N - \varepsilon' N] \times [D]$  and map  $F^*(f, x, y) = (f, x', y') \in Y_0$ .

Note that the evaluation of (14) might be ill-behaved in the following cases. Suppose  $x \in [a_i]$  and let  $x' := f_i(x)$ . If  $x' \notin S_i$  or  $g_i(x') \neq x$ , then we know that  $x'$  is a **(Violation of  $|S_i| \geq a_i$ )** and we simply let  $F^*(f, x, y) := \perp$ . Otherwise, if  $(x', y)$  witnesses that  $(F_i, G_i)$  is not an injection-surjection pair, then  $S_i$  is a distinguisher for  $\text{PRG}_f$ . Let  $Y_1 := [K] \times [\ell] \times [2N] \times [D]$ , we define  $F^*(f, x, y) := (\text{Comp}^{S_i}(f, x', y), i, x, y) \in Y_1$ . If both cases above do not happen, we define  $F^*(f, x, y) := (f, x', y') \in Y_0$  as usual.

- **Case II:** Suppose that there exists  $1 \leq i < j \leq \ell$  such that  $v_{i,j} > a_{i,j} + 2\varepsilon' N$ . If  $x \notin [v_{i,j}]$ , then we let  $x' := x - \varepsilon' N$  and  $y' := y$ ; otherwise we feed  $(x, y)$  into

$$[v_{i,j}] \times [D] \xrightarrow[F_{i,j}]{G_{i,j}} ((S_i \cap S_j) \dot{\cup} [\varepsilon' N]) \xrightarrow[g_{i,j} \times [D]]{f_{i,j} \times [D]} [a_{i,j} + \varepsilon' N] \times [D] \quad (15)$$

to obtain  $(x', y') \in [a_{i,j} + \varepsilon' N] \times [D]$ . We let  $F^*(f, x, y) := (f, x', y') \in Y_0$ .

Similarly, the evaluation of (15) might be ill-behaved in the following cases. Suppose  $x \in [v_{i,j}]$ . If  $(x, y)$  witnesses that  $(G_{i,j}, F_{i,j})$  is not a valid injection-surjection pair, then  $S_i \cap S_j$  is a distinguisher for  $\text{PRG}_f$ ; in this case, letting  $Y_2 := [K] \times [\ell]^2 \times [2n] \times [D]$ , we map  $F^*(f, x, y) := (\text{Comp}^{S_i \cap S_j}(f, x, y), i, j, x, y) \in Y_2$ . Otherwise, let  $(x', y') := G_{i,j}(x, y)$ , if  $x' \in S_i \cap S_j$  but  $x'$  witnesses that  $(g_{i,j}, f_{i,j})$  is not a valid injection-surjection pair, then  $x'$  is a **(Violation of  $|S_i \cap S_j| \leq a_{i,j}$ )** and we simply let  $F^*(f, x, y) := \perp$ . If both cases above do not happen, we define  $F^*(f, x, y) = (f, x', y') \in Y_0$  as usual.

- **Case III:** Suppose that  $v > \tilde{a} - \varepsilon N + 2\varepsilon' N$ . If  $x \notin [v]$ , then we let  $x' := x - \varepsilon' n$  and  $y' := y$ ; otherwise we feed  $(x, y)$  into

$$[v] \times [D] \xrightarrow[F]{G} (S \dot{\cup} [\varepsilon' N]) \times [D] \xrightarrow[\tilde{f} \times [D]]{\tilde{g} \times [D]} [\tilde{a} - \varepsilon N + \varepsilon' N] \times [D] \quad (16)$$

to obtain  $(x', y') \in [\tilde{a} - \varepsilon N + \varepsilon' N] \times [D]$ . We let  $F^*(f, x, y) = (f, x', y') \in Y_0$ .

Similarly, the evaluation of (16) on  $(x, y)$  might be ill-behaved in the following cases. Suppose  $x \in [v]$ . If  $(x, y)$  witnesses that  $(G, F)$  is not a valid injection-surjection pair, then  $S$  is a valid distinguisher for  $\text{PRG}_f$ ; in this case, letting  $Y_3 := [K] \times [2N] \times [D]$ , we map  $F^*(f, x, y) := (\text{Comp}^S(f, x, y), x, y) \in Y_3$ . Otherwise, let  $(x', y') := G(x, y)$ , if  $x' \in S$  but  $x'$  witnesses that  $(\tilde{g}, \tilde{f})$  is not a valid injection-surjection pair, then  $x'$  is a **(Violation of  $\left| \bigcup_{i \in [\ell]} S_i \right| \leq \tilde{a} - \varepsilon N$ )** and we let  $F^*(f, x, y) := \perp$ . If both cases above do not happen, we define  $F^*(f, x, y) := (f, x', y') \in Y_0$  as usual.

Let  $Y$  be the disjoint union  $Y := Y_0 \dot{\cup} Y_1 \dot{\cup} Y_2 \dot{\cup} Y_3 \dot{\cup} \{\perp\}$ , then

$$\frac{|Y|}{|X|} \leq \frac{N'(2N - \varepsilon' N)D + K \cdot 2\ell^2 \cdot 2N \cdot D + 1}{N' \cdot 2N \cdot D} \leq 1 - \varepsilon'/2 + (K \cdot 2\ell^2 + 1)/N' \leq 1 - \varepsilon'/4.$$

We have described a function  $F^* : X \rightarrow Y$  and it remains to describe  $G^* : Y \rightarrow X$ . The **LOSSY-CODE** instance  $(F^*, G^*)$  reduces to a standard **LOSSY-CODE** instance (of stretch  $[2t] \rightleftharpoons [t]$ ) in decision tree depth  $O(\log(1/\varepsilon')) \leq \text{polylog}(N)$ . Given an input in  $Y$ :

- If the input is  $(f, x', y') \in Y_0$ , then one of the above three cases happen for  $f$ ; depending on this, we map  $(x', y')$  back to  $(x, y)$  via the appropriate surjection. For example, in case I: If  $x' \notin [v_i + \varepsilon' n]$  then we let  $x := x' + \varepsilon' n$  and  $y' := y$ ; otherwise we let  $(x'', y) := G_i(x', y')$  and  $x := g_i(x')$ .
- If the input is  $(\hat{f}, i, x, y) \in Y_1$ , then we recover  $f := \text{Decomp}^{S_i}(\hat{f})$  and return  $(f, x, y)$ .
- If the input is  $(\hat{f}, i, j, x, y) \in Y_2$ , then we recover  $f := \text{Decomp}^{S_i \cap S_j}(\hat{f})$  and return  $(f, x, y)$ .
- If the input is  $(\hat{f}, x, y) \in Y_3$ , then we recover  $f := \text{Decomp}^S(\hat{f})$  and return  $(f, x, y)$ .
- We do not care about the value of  $G^*(\perp)$ ; we map it to an arbitrary value.

Finally, we need to argue that this is a correct reduction. Let  $(f, x, y) \in X$ . If  $F^*(f, x, y) \in Y_0$ , then the injection-surjection pairs ((14), (15), (16)) are well-behaved, hence  $G^*(F^*(f, x, y)) = (f, x, y)$ ; if  $F^*(f, x, y) \in Y_1 \cup Y_2 \cup Y_3$ , then the compression  $(\text{Comp}^O(f, x, y))$  for the suitable oracle  $O$  works correctly, hence  $G^*(F^*(f, x, y)) = (f, x, y)$  as well. Therefore, if  $(f, x, y)$  is a solution of the **LOSSY-CODE** instance, then  $F^*(f, x, y) = \perp$ . As discussed above, in this case, we will find a solution of **INCLUSION-EXCLUSION**.  $\square$

#### 6.2.4 Conclusion: **LOSSY**-Completeness

Finally, it is easy to see that the problems we considered (AMGM-LC, Dual-AMGM-LC, and **INCLUSION-EXCLUSION**) are at least as hard as **LOSSY-CODE**, hence they are **LOSSY**-complete.

**Theorem 6.6.** The following problems are **LOSSY**-complete:

- $c$ -AMGM-LC for every constant  $c > 1$ ;
- $c$ -dual-AMGM-LC for every  $0 < c < 2$ ;
- **INCLUSION-EXCLUSION**.

## 7 Dense Linear Ordering

Finally, we show that the dense version of the Linear Ordering Principle reduces to LOSSY-CODE. The Linear Ordering Principle was recently studied by Korten and Pitassi [KP24], where they showed that AVOID reduces to Linear Ordering. In the TFNP world, we show the opposite reduction and prove that Dense Linear Ordering reduces to Lossy Code. This problem has been studied in proof complexity [Rii01, AD08, Gry19, CdRN<sup>+</sup>23] as well.

**DENSE-LINEAR-ORDERING.** The input consists of the descriptions of a linear ordering  $\prec$  over  $N$  elements and a *median function*  $\text{med} : [N] \times [N] \rightarrow [N]$ . Without loss of generality, we may assume that for  $x \neq y \in [N]$ , exactly one of  $(x \prec y)$  and  $(y \prec x)$  is true, and that  $\text{med}(x, y) = \text{med}(y, x)$ . (That is,  $\prec$  is represented by a string of  $\binom{N}{2}$  bits and  $\text{med}$  is represented by a list of  $\binom{n}{2}$  elements in  $[N]$ .) A solution is one of the following.

- s1.  $x, y, z \in [N]$  such that  $x \prec y$ ,  $y \prec z$ , and  $z \prec x$ ; or (Transitivity Violation)
- s2.  $x, y \in [N]$  such that  $x \prec y$ , but neither  $x \prec \text{med}(x, y)$  nor  $\text{med}(x, y) \prec y$ . (Invalid Median)

**Theorem 7.1.** DENSE-LINEAR-ORDERING reduces to LOSSY-CODE.

*Proof.* Let  $(\prec, \text{med})$  be an input of DENSE-LINEAR-ORDERING over a universe  $\mathcal{U}$  of size  $N$ .

Fix some arbitrary  $l_0, r_0$  in advance such that  $l_0 \prec r_0$ , and let  $\ell := 4 \log N$ . Consider the following LOSSY-CODE instance  $(f, g)$  between  $\mathcal{U}$  and  $\{\text{L}, \text{R}\}^{\leq \ell}$ .

---

**Algorithm 5**  $f : \mathcal{U} \rightarrow \{\text{L}, \text{R}\}^{\leq \ell}$

---

```

1: function  $f(m)$ 
2:    $\sigma \leftarrow$  the empty string
3:   for  $i \leftarrow 1$  to  $\ell$  do
4:      $m_{i-1} \leftarrow \text{med}(l_{i-1}, r_{i-1})$ 
5:     if  $m_{i-1} = m$  then
6:       return  $\sigma$ 
7:     else if  $m \prec m_{i-1}$  then
8:        $(l_i, r_i) \leftarrow (l_{i-1}, m_{i-1})$ ,  $\sigma \leftarrow \sigma \circ \text{L}$ 
9:     else  $\triangleright m_{i-1} \prec m$ 
10:     $(l_i, r_i) \leftarrow (m_{i-1}, r_{i-1})$ ,  $\sigma \leftarrow \sigma \circ \text{R}$ 
11:   return  $\sigma$   $\triangleright$  regardless of whether we have arrived at  $m$ 

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**Algorithm 6**  $g : \{\text{L}, \text{R}\}^{\leq \ell} \rightarrow \mathcal{U}$

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```

1: function  $g(\sigma)$ 
2:   for  $i \leftarrow 1$  to  $|\sigma|$  do
3:      $m_{i-1} \leftarrow \text{med}(l_{i-1}, r_{i-1})$ 
4:     if  $\sigma_i = \text{L}$  then
5:        $(l_i, r_i) \leftarrow (l_{i-1}, m_{i-1})$ 
6:     else  $\triangleright \sigma_i = \text{R}$ 
7:        $(l_i, r_i) \leftarrow (m_{i-1}, r_{i-1})$ 
8:   return  $\text{med}(l_{|\sigma|}, r_{|\sigma|})$ 

```

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In the following discussion, we assume that throughout the executions of  $f$  and  $g$ , we always have  $l_i \prec r_i$  for each valid  $i$ . This is because otherwise we can find an (Invalid Median): Let  $i$  be the smallest index such that  $l_i \not\prec r_i$ , then  $i \geq 1$  and  $l_{i-1} \prec r_{i-1}$ . Either we have  $(l_i, r_i) = (l_{i-1}, m_{i-1})$ , or we have  $(l_i, r_i) = (m_{i-1}, r_{i-1})$ . In both cases,  $(l_{i-1}, r_{i-1})$  has an (Invalid Median).

Consider the following scenario. Suppose that  $g(\sigma) = v$ , but during the execution of  $g(\sigma)$ , we encountered some interval  $(l_i, r_i)$  such that either  $(l_i \not\prec v)$  or  $(v \not\prec r_i)$ . We argue that in this scenario, it is easy to find a solution of  $(\prec, \text{med})$ . Suppose  $l_i \not\prec v$ ; the case that  $v \not\prec r_i$  can be handled symmetrically.

- If  $l_{|\sigma|} \not\prec v$  then,  $(l_{|\sigma|}, r_{|\sigma|})$  has an (Invalid Median).

- Otherwise there is an index  $j \in [i, |\sigma|)$  such that  $l_j \not\prec v$  but  $l_{j+1} \prec v$ . It follows that  $l_j \neq l_{j+1}$ , which implies that  $l_{j+1} = \text{med}(l_j, r_j)$ .
  - If  $l_j \not\prec l_{j+1}$  then we have an **(Invalid Median)**  $(l_j, r_j)$ .
  - Otherwise, since  $l_{j+1} \prec v$  and  $l_j \prec l_{j+1}$ , we have  $v \neq l_j$ . Since  $l_j \not\prec v$ , we have  $v \prec l_j$ . Now we have a **(Transitivity Violation)**  $(l_j, l_{j+1}, v)$  where  $v \prec l_j$ ,  $l_j \prec l_{j+1}$ , and  $l_{j+1} \prec v$ .

Now we prove the correctness of our reduction. That is, given any string  $\sigma \in \{\text{L}, \text{R}\}^{\leq \ell}$  such that  $f(g(\sigma)) \neq \sigma$ , we can find a solution for DENSE-LINEAR-ORDERING. Let  $v := g(\sigma)$  and  $\sigma' := f(v)$ , then  $\sigma' \neq \sigma$ . Let  $i$  be the smallest index such that  $\sigma'_i \neq \sigma_i$ . In particular, if  $\sigma'$  is a prefix of  $\sigma$  then we define  $i := |\sigma'| + 1$ . (Note that it cannot be the case that  $\sigma$  is a prefix of  $\sigma'$ , as otherwise the execution of  $f(v)$  would have reached the element  $v$  in the  $|\sigma|$ -th step and returned  $\sigma$  instead of  $\sigma'$ .) It follows that the first  $i - 1$  rounds of  $f(v)$  and  $g(\sigma)$  produce the same intervals  $\{(l_j, r_j)\}_{0 \leq j < i}$ . Assume that  $\sigma_i = \text{L}$ ; the case that  $\sigma_i = \text{R}$  is symmetric. Let  $(l_i^g, r_i^g)$  denote the interval  $(l_i, r_i)$  in the execution of  $g(\sigma)$ , then  $l_i^g = l_{i-1}$  and  $r_i^g = m_{i-1} = \text{med}(l_{i-1}, r_{i-1})$ .

- If  $i = |\sigma'| + 1$ , then  $m_{i-1} = v = g(\sigma)$ .
- Otherwise,  $\sigma'_i = \text{R}$  and hence  $m_{i-1} \prec v = g(\sigma)$ .

In either case, we have found some  $(l_i^g, r_i^g)$  during the execution of  $g(\sigma)$  such that  $v \not\prec r_i^g$ . By the previous discussion, we can find a solution of  $(\prec, \text{med})$ .  $\square$

## 8 Open Problems

We end with some future directions. The main problem left open by this work is to exhibit a natural problem in  $\text{TFZPP}^{dt}$  which is not reducible to LOSSY-CODE; we conjecture that NEPHEW is such a problem. Some additional open questions are the following:

- Find a TFZPP upper bound for BERTRAND-CHEBYSHEV, i.e., a natural problem in TFZPP to which BERTRAND-CHEBYSHEV reduces. The best upper bound we are aware of is only LOSSY<sup>FACTORIZING</sup> [PWW88, Kor22], which is in LOSSY<sup>PPA</sup> and LOSSY<sup>PWPP</sup> under the generalized Riemann Hypothesis [Jeř16]. Unfortunately, none of these upper bound classes are in TFZPP.
- Find a TFZPP upper bound for the following problem, which we call RAZBOROV-SMOLENSKY [Raz87, Smo87]: The input is an  $\text{AC}^0[2]$  circuit  $C$  of depth  $d$  and size at most  $2^{n^{1/10d}}$  that attempts to compute MAJ (the Majority function), and the goal is to output an instance  $x \in \{0, 1\}^n$  such that  $C(x) \neq \text{MAJ}(x)$ . Since MAJ is average-case hard against such circuits, this problem sits in TFZPP. This problem is trivially solvable in deterministic quasi-polynomial time (note that the naïve algorithm runs in  $2^{O(n)}$  time while the input size is  $2^{n^{\Omega(1)}}$ ), hence we are interested in the regime where only polynomial-time reductions are allowed. We are not aware of any syntactic subclass of TFZPP that contains this problem.
- Is BIJ-LOSSY-CODE  $\in \text{PPAD}$ ? Observe that BIJ-LOSSY-CODE is equivalent to END-OF-LINE with half of the vertices designated as distinguished sources. The simple argument showing LOSSY-CODE  $\in \text{PPADS}$ , that is, output the solution returned by the PPAD solver on the original graph, does not work here, since the PPAD solver may return one of the distinguished sources. Recently, Goldberg and Hollender [GH21] gave an involved proof that END-OF-LINE with  $k$  distinguished sources belongs to PPAD when  $k = \text{polylog}(N)$ , where  $N$  denotes the size of the graph. However, their argument does not extend to the case that  $k = \text{poly}(N)$  since the PPAD instance they constructed has size  $N^{\Omega(k)}$ .

- Can BINARY-EMPTY-CHILD be separated from BIJ-LOSSY-CODE?
- What is the relationship between DENSE-LINEAR-ORDERING and BIJ-LOSSY-CODE?

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## A Herbrandization

Herbrandization is a basic construction in logic. Roughly speaking, any  $\text{TF}\Sigma_2^P$  problem  $L$  can be captured by a logical formula  $\forall x \exists y \forall z \varphi(x, y, z)$ ,<sup>12</sup> where the task of  $L$  is, given  $x$ , to find a  $y$  such that  $\forall z \varphi(x, y, z)$  holds. To Herbrandize this formula, we add another function  $h$  (treated as an input oracle) and consider the formula  $\forall x \exists y \varphi(x, y, h(y))$ . One can then define a  $\text{TFNP}$  problem by treating  $h$  as a first-order variable like  $x$ , where the task is, given  $x$  and  $h$ , to find a  $y$  such that  $\varphi(x, y, h(y))$  holds.

<sup>12</sup>Formally, they are called “ $\forall\Sigma_2^b$ -formulas”, where the subscript 2 stands for two alternations ( $\forall\exists\forall$ ) and the superscript  $b$  stands for “bounded”, i.e., the lengths of  $x, y, z$  are polynomially related and  $\varphi$  is a polynomial-time predicate.

<b>TFΣ<sub>2</sub><sup>P</sup> search problem</b>	<b>TFNP problem via Herbrandization</b>
$\forall x \exists y \forall z \varphi(x, y, z)$	$\forall x, h \exists y \varphi(x, y, h(y))$
AVOID: $\forall D \exists x \forall y D(y) \neq x$	LOSSY-CODE: $\forall C, D \exists x D(C(x)) \neq x$
(1): $\forall F \exists x \forall y (F(F(y)) \neq F(x) \vee F(y) = x)$	NEPHEW: $\forall F, G \exists x (F(F(G(x))) \neq F(x) \vee F(G(x)) = x)$

**Table 1:** Some examples of TFNP problems via Herbrandization.

## B Proof Complexity Characterizations of Randomized Reductions

In this section we prove [Theorem 3.4](#), which we restate next.

**Theorem B.1.** If a proof system  $\mathcal{P}$  is characterized by the total search problems reducible to  $R \in \text{TFNP}^{dt}$ , then  $r\mathcal{P}$  is characterized by the total search problems that are randomized-reducible to  $R$ .

*Proof.* Fix a complexity  $c$   $r\mathcal{P}$  proof  $\mathcal{D}$  of a CNF formula  $H$ . We will construct a complexity  $\Theta(c)$  randomized reduction from  $\text{SEARCH}_H$  to a complete problem  $\text{SEARCH}_F$  for  $\mathcal{C}$ . On input  $x \in \{0, 1\}^n$  the reduction first samples  $(\Pi, B)$  from the distribution  $\mathcal{D}$  given by the  $r\mathcal{P}$  proof, where  $\Pi$  is a complexity  $c$   $\mathcal{P}$ -proof of  $H \wedge B$ . Since by assumption  $\mathcal{P}$  is characterized by  $\mathcal{C}$ , this implies that there is a complexity  $O(c)$  reduction  $\mathcal{T} = (T, \{T_o\})$  from  $\text{SEARCH}_{H \wedge B}$  to  $\text{SEARCH}_F$ . Relabel each leaf of an output decision tree  $T_o$  in  $\mathcal{T}$ , which is labelled with a clause of  $B$ , by  $\perp$ , indicating a failure event of the randomized reduction.

Observe that property (1) (correctness) of a randomized reduction to  $\text{SEARCH}_H$  is satisfied. It remains to argue that property (2) (error probabilities) is also satisfied. This follows since the reduction was constructed from a  $r\mathcal{P}$  proof. Indeed, the probability that the reduction fails is the probability that we sampled a reduction  $\mathcal{T} = (T, \{T_o\})$  and the leaf of the output decision tree that we arrive at when following  $x$  is labelled by  $\perp$ . By construction, we arrive at a  $\perp$  leaf only if we falsify a clause of the corresponding CNF  $B$ . However, by the definition of an  $r\mathcal{P}$  proof, for every  $x$  the probability that every clause in  $B$  is satisfied by  $x$  is at least  $2/3$ .

For the converse, let  $\text{SEARCH}_F$  be a  $\mathcal{C}$ -complete problem and let  $\mathcal{D}$  be a randomized reduction from  $\text{SEARCH}_H$  to  $\text{SEARCH}_F$  of complexity  $c$ . We will argue that each  $\mathcal{T} \sim \mathcal{D}$  is a deterministic reduction from  $\text{SEARCH}_{H \wedge B}$  to  $\text{SEARCH}_F$  for some CNF formula  $B$  of width  $O(c^2)$ . Because  $\mathcal{C}$  is characterized by  $\mathcal{P}$ , we will obtain a  $\mathcal{P}$  proof of  $H \wedge B$ , and putting these together, a  $r\mathcal{P}$  proof of  $H$ .

Let  $F = C_1 \wedge \dots \wedge C_m$  and let  $\mathcal{T} \sim \mathcal{D}$  where  $\mathcal{T} := (\{T_i\}_{i \in [n]}, \{T_o\}_{o \in [m]})$ . Following [\[BFI23\]](#), let the *reduced formula*  $F_{\mathcal{T}}$  be the CNF formula obtained as follows: for each clause  $C \in F$ , let the decision tree  $T^C$  be obtained by sequentially running the decision trees  $T_i$  for each  $i \in \text{vars}(C)$  to obtain an assignment  $\alpha \in \{0, 1\}^{\text{vars}(C)}$ . If  $C(\alpha) = b \in \{0, 1\}$  then label this a “ $b$ -leaf”, for  $b \in \{0, 1\}$ . Say that a root-to-leaf path  $p \in T^C$  is a  $b$ -path if it ends at a  $b$ -leaf. Define

$$C(\mathcal{T}) := \bigwedge_{\text{0-path } p \in T^C} \neg p$$

In words,  $C(\mathcal{T})$  says that the clause  $C$ , after substituting  $\mathcal{T}$  for the variables, is never falsified. The reduced CNF formula is

$$F_{\mathcal{T}} := \bigwedge_{o \in [m]} \left( C_o(\mathcal{T}) \vee \bigwedge_{p \in T_o} \neg p \right).$$

$F_{\mathcal{T}}$  formalizes the definition of a reduction (Equation 2) by  $\mathcal{T}$  to  $\text{SEARCH}_F$ —if we falsify  $C_o(\mathcal{T})$  and follow path  $p$  in  $T_o$  then the label of the leaf of  $p$  is a valid solution to the search problem reducing to  $\text{SEARCH}_F$  by  $\mathcal{T}$ . Hence,  $\mathcal{T}$  is a reduction from a CNF formula  $H \wedge B$  to  $F$  iff each clause of  $F_{\mathcal{T}}$  is a weakening<sup>13</sup> of a clause of  $H \wedge B$ .

Then, knowing  $H$ , we can recover  $B$  as follows: let  $B$  be the set of all clauses of  $F_{\mathcal{T}}$  which are not a weakening of any clause of  $H$ . Then  $\mathcal{T}$  is a reduction from  $\text{SEARCH}_{H \wedge B}$  to  $\text{SEARCH}_F$ . Note that the width of the clauses in  $B$  is at most  $O(c^2)$  as every clause in  $F$  has width  $O(c)$ , the trees in  $\mathcal{T}$  have depth  $O(c)$ , and we have substituted the decision trees for the variables of the clause.

It remains to argue that for every  $x \in \{0, 1\}^n$ ,  $\Pr_{(\Pi, B) \sim \mathcal{D}}[B(x) = 1] \geq 2/3$ . This is immediate from the fact that  $\mathcal{T}$  is a randomized reduction to  $\text{SEARCH}_F$ . Indeed, each clause  $K \in F_{\mathcal{T}}$  comes from some  $C_o(\mathcal{T}) \vee \neg p$  for  $p \in T_o$  and some  $o \in [m]$ . That is,  $K = \neg p^* \vee \neg p$  for some 0-path  $p^* \in T^C$ . Hence, by the definition of a randomized reduction,

$$\begin{aligned} 2/3 &\leq \Pr_{\mathcal{T} \sim \mathcal{D}} [\forall o \in [m] : (o, T(x)) \notin \text{SEARCH}_F \vee T_o(x) \neq \perp] \\ &= \Pr_{\mathcal{T} \sim \mathcal{D}} [\forall o \in [m] : C_o(\mathcal{T}(x)) \neq 0 \vee T_o(x) \neq \perp] \\ &= \Pr_{\mathcal{T} \sim \mathcal{D}} [\forall o \in [m], \forall \text{ 0-paths } p^* \in T^{C_o}, \forall \perp\text{-paths } p \in T_o : \neg p^*(x) = 1 \vee \neg p(x) = 1] \\ &= \Pr_{\mathcal{T} \sim \mathcal{D}} [\forall K \in B : K(x) = 1]. \end{aligned} \quad (B \text{ are clauses of } F_{\mathcal{T}})$$

□

## C Proof of Theorem 6.2

**Weak designs.** We say that  $I_1, I_2, \dots, I_m \subseteq [d]$  is a *weak  $(\ell, \rho)$ -design* if:

- For every  $i \leq m$ ,  $|I_i| = \ell$ ; and
- For every  $i \leq m$ ,

$$\sum_{j < i} 2^{|S_i \cap S_j|} \leq \rho \cdot (m-1).$$

**Theorem C.1** ([RRV02]). For every  $\ell, m \in \mathbb{N}$  and  $\rho > 1$ , there is a weak  $(\ell, \rho)$ -design  $S_1, S_2, \dots, S_m \subseteq [d]$  with

$$d = \left\lceil \frac{\ell}{\ln \rho} \right\rceil \cdot \ell.$$

Moreover, such a family can be found in deterministic time  $\text{poly}(m, d)$ .

**List-decodable codes.** A pair of functions  $(\text{Enc}, \text{Dec})$  is called an  $(L, 1/2 - \varepsilon)$ -list-decodable code if:

- $\text{Enc} : \{0, 1\}^n \rightarrow \{0, 1\}^{2^\ell}$  and  $\text{Dec} : \{0, 1\}^{2^\ell} \rightarrow (\{0, 1\}^n)^L$  are computable in deterministic polynomial time, and
- for every  $x \in \{0, 1\}^n$  and  $y \in \{0, 1\}^{2^\ell}$  such that  $y$  is  $(1/2 - \varepsilon)$ -close to  $\text{Enc}(x)$ ,  $\text{Enc}(x)$  appears in the list  $\text{Dec}(y)$ .

**Theorem C.2** ([STV01]). For every  $n \in \mathbb{N}$  and  $\varepsilon > 0$ , there exists an  $(L, 1/2 - \varepsilon)$ -list-decodable code with  $\ell = O(\log(n/\varepsilon))$  and  $L = \text{poly}(1/\varepsilon)$ .

<sup>13</sup>A clause  $C$  is a weakening of a clause  $D$  if the literals of  $D$  are a subset of the literals of  $C$ .

In what follows, for notational convenience, we will think of length- $2^\ell$  strings  $f \in \{0,1\}^{2^\ell}$  as (the truth tables of)  $\ell$ -bit Boolean functions  $f : \{0,1\}^\ell \rightarrow \{0,1\}$ .

**Theorem 6.2.** Let  $n, m \in \mathbb{N}$ ,  $\varepsilon > 0$ , and  $\rho > 1$  be parameters. Let  $d := O\left(\frac{\log^2(nm/\varepsilon)}{\log \rho}\right)$  and  $k := d + (\rho + 1)(m - 1) + O(\log(m/\varepsilon))$ . Let  $N := 2^n$ ,  $M := 2^m$ ,  $K := 2^k$ , and  $D := 2^d$ .

Then there is a  $(k, \varepsilon)$ -reconstructive generator  $\text{PRG} : [N] \times [D] \rightarrow [M]$  with  $\text{poly}(\rho mn/\varepsilon)$ -time deterministic oracle algorithms  $G_<, H_<, G_>, H_>, \text{Comp}, \text{Decomp}$  such that the following holds. For every set  $S \subseteq [M]$ , every  $f \in [N]$ , and every input  $w$  witnessing that either

$$[val] \times [D] \xrightarrow[G_<^S(f,-)]{H_<^S(f,-)} (S \dot{\cup} [\varepsilon M]) \times [D] \quad \text{or} \quad S \times [D] \xrightarrow[G_>^S(f,-)]{H_>^S(f,-)} ([val] \dot{\cup} [\varepsilon M]) \times [D]$$

is not an injection-surjection pair (where  $val := |S \cap \text{PRG}_f| \cdot \frac{M}{D}$ ), we have  $\text{Comp}^S(f, w) \in [K]$  and

$$\text{Decomp}^S(\text{Comp}^S(f, w)) = f.$$

*Proof.* Let  $\varepsilon'$  be the biggest (inverse) power of 2 such that  $\varepsilon' \leq \varepsilon/m$ . Let  $(\text{Enc}, \text{Dec})$  be an  $(L, 1/2 - \varepsilon')$ -list-decodable code guaranteed by [Theorem C.2](#) with  $\ell = O(\log n/\varepsilon') = O(\log(nm/\varepsilon))$  and  $L \leq \text{poly}(1/\varepsilon') \leq \text{poly}(m/\varepsilon)$ . Let  $I_1, I_2, \dots, I_m \subseteq [d]$  be a weak  $(\ell, \rho)$ -design guaranteed by [Theorem C.1](#) with  $d = O(\ell^2/\log \rho)$ . Given  $f \in \{0,1\}^n$  and  $z \in \{0,1\}^d$  as inputs, the generator first computes  $\tilde{f} := \text{Enc}(f)$ , and then outputs

$$\text{PRG}(f, z) := (\tilde{f}(z|_{I_1}), \tilde{f}(z|_{I_2}), \dots, \tilde{f}(z|_{I_m})).$$

The classical proof of Nisan–Wigderson [[NW94](#)] shows that for every  $S \subseteq \{0,1\}^m$  and every  $f \in \{0,1\}^n$  that is worst-case hard against  $S$ -oracle circuits,  $f$  provides an additive approximation of  $|S|$ , i.e.,

$$\left| \frac{|S \cap \text{PRG}_f|}{D} - \frac{|S|}{M} \right| \leq \varepsilon.$$

The *proof* of the above fact goes through a *hybrid* argument and considers the following intermediate generators. For each  $0 \leq i \leq m$ , let  $\text{Hyb}_i : \{0,1\}^d \times \{0,1\}^m \rightarrow \{0,1\}^m$  denote the generator that takes  $z \in \{0,1\}^d$  and  $r \in \{0,1\}^m$  as inputs, and outputs

$$\text{Hyb}_i(z, r) := (\tilde{f}(z|_{I_1}), \dots, \tilde{f}(z|_{I_i}), r_{i+1}, \dots, r_m).$$

Let  $V_i := \{(z, r) : \text{Hyb}_i(z, r) \in S\}$ ; intuitively,  $|V_i|$  is an estimation of  $|S| \cdot 2^d$  by the generator  $\text{Hyb}_i$ . Suppose  $f$  is hard, then for every  $1 \leq i \leq m$ ,  $|V_{i-1}|$  is close to  $|V_i|$ . It follows that  $|V_0|$  is close to  $|V_m|$ . Since  $|V_0| = 2^d \cdot |S|$  and  $|V_m| = |S \cap \text{PRG}_f| \cdot 2^m = val \cdot 2^d$ ,  $val$  is a good estimation of  $|S|$ .

In a nutshell, the proof of [[Jeř07a](#), Theorem 2.7] proceeds by constructing injection-surjection pairs witnessing  $|V_{i-1}| \lesssim |V_i|$  and  $|V_{i-1}| \gtrsim |V_i|$  for each  $i$ . Composing all these injection-surjection pairs gives the final injection-surjection pairs witnessing  $|V_0| \lesssim |V_m|$  and  $|V_0| \gtrsim |V_m|$  respectively.

Fix  $1 \leq i \leq m$ , we now aim to construct injection-surjection pairs witnessing the inequalities  $|V_{i-1}| \lesssim |V_i|$  and  $|V_{i-1}| \gtrsim |V_i|$ . That is, letting  $diff := \varepsilon' \cdot 2^{m+d}$ , we will construct injection-surjection pairs  $V_i \xrightarrow[G_i]{H_i} V_{i-1} \dot{\cup} [diff]$  and  $V_{i-1} \xrightarrow[G'_i]{H'_i} V_i \dot{\cup} [diff]$  that depends on  $f$ . Moreover, if  $f$  is indeed a “hard function”, then these injection-surjection pairs will be valid, i.e.,  $G_i \circ H_i$  is the identity map on  $V_i$  and  $G'_i \circ H'_i$  is the identity map on  $V_{i-1}$ .

Let  $z \in \{0,1\}^d$  and  $r \in \{0,1\}^m$ , we denote  $z' := z|_{I_i}$  and  $\text{aux} := (z|_{[d] \setminus I_i}, r_{[m] \setminus i})$ . Note that there is a one-to-one correspondence between  $(z, r)$  and  $(z', r_i, \text{aux})$ . Now given  $i, \text{aux}$ , we define

$$X_{i, \text{aux}} := \{(z', r_i) : (\tilde{f}(z|_{I_1}), \tilde{f}(z|_{I_2}), \dots, \tilde{f}(z|_{I_{i-1}}), r_i, r_{i+1}, \dots, r_n) \in S\} \text{ and}$$

$$Y_{i,\text{aux}} := \{(z', b) : (z', \tilde{f}(z')) \in X_{i,\text{aux}}\}.$$

Then,  $V_{i-1} = \bigcup_{\text{aux}} (X_{i,\text{aux}} \times \{\text{aux}\})$  and  $V_i = \bigcup_{\text{aux}} (Y_{i,\text{aux}} \times \{\text{aux}\})$ . To show that  $|V_{i-1}| \approx |V_i|$ , it suffices to show that  $|X_{i,\text{aux}}| \approx |Y_{i,\text{aux}}|$  for every  $\text{aux}$  (under the assumption that  $f$  is “hard”); this is exactly what the next claim shows.

**Claim C.3.** If  $||X_{i,\text{aux}}| - |Y_{i,\text{aux}}|| > \varepsilon' 2^{\ell+1}$ , then given  $(i, \text{aux})$  and additional  $\rho \cdot (m-1) + 2$  advice bits, it is possible to recover a string  $\tilde{f}_{\text{aux}}$  that is  $(1/2 + \varepsilon')$ -close to  $\tilde{f}$  in deterministic  $\text{poly}(\rho m, 2^\ell)$  time with oracle access to  $S$ . Moreover, given  $(i, \text{aux})$  and  $\tilde{f}$ , the additional advice bits can be computed in deterministic  $\text{poly}(\rho m, 2^\ell)$  time with oracle access to  $S$ .

*Proof Sketch.* For every  $b \in \{0, 1\}$ , define a string  $\tilde{f}^b \in \{0, 1\}^{2^\ell}$ , where for every  $z' \in \{0, 1\}^\ell$ , the  $z'$ -th bit of  $\tilde{f}^b$  is 1 if and only if  $(z', b) \in X_{i,\text{aux}}$ . It can be shown that

$$|X_{i,\text{aux}}| - |Y_{i,\text{aux}}| = \Delta(\tilde{f}^1, \tilde{f}) - \Delta(\tilde{f}^0, \tilde{f}),$$

where  $\Delta(\cdot, \cdot)$  denotes the Hamming distance of two binary strings. Since  $||X_{i,\text{aux}}| - |Y_{i,\text{aux}}|| > \varepsilon' 2^{\ell+1}$ , there must be some  $b \in \{0, 1\}$  such that  $\Delta(\tilde{f}^b, \tilde{f}) \notin [(1/2 - \varepsilon')2^\ell, (1/2 + \varepsilon')2^\ell]$ .

Now suppose that  $\tilde{f}$  is fixed and  $(i, \text{aux})$  is given. For each  $j < i$ ,  $\tilde{f}(z|_{I_j})$  is a function over  $z'$  that only depends on  $|S_i \cap S_j|$  bits of  $z'$ . Hence, the truth table of this function can be recorded in  $2^{|S_i \cap S_j|}$  bits. If we write down the truth tables of  $\tilde{f}(z|_{I_j})$  for every  $j < i$  as advice, this only costs

$$\sum_{j < i} 2^{|S_i \cap S_j|} \leq \rho \cdot (m-1)$$

advice bits. We append two additional advice bits  $b, b' \in \{0, 1\}$ , where  $b$  indicates that  $\Delta(\tilde{f}^b, \tilde{f}) \notin [(1/2 - \varepsilon')2^\ell, (1/2 + \varepsilon')2^\ell]$  and  $b'$  indicates whether  $\Delta(\tilde{f}^b, \tilde{f})$  is above  $1/2$  or not. It is easy to see that we can recover a string that is  $(1/2 + \varepsilon')$ -close to  $\tilde{f}$  given  $(i, \text{aux})$  and these advice bits; moreover, these advice bits can be computed in deterministic polynomial time given  $(i, \text{aux})$  and  $f$  as inputs.  $\diamond$

Composing the above claim with the list-decodable code  $(\text{Enc}, \text{Dec})$ , we obtain the following corollary:

**Corollary C.4.** If  $||X_{i,\text{aux}}| - |Y_{i,\text{aux}}|| > \varepsilon' 2^{\ell+1}$ , then given  $(i, \text{aux})$  and additional  $\rho \cdot (m-1) + \log L + 2$  advice bits, it is possible to compute  $f$  in deterministic  $\text{poly}(\rho m, 2^\ell)$  time with oracle access to  $S$ . Moreover, given  $(i, \text{aux})$  and  $f$ , the additional advice bits can be computed in deterministic  $\text{poly}(\rho m, 2^\ell)$  time with oracle access to  $S$ .  $\diamond$

Let  $\text{Decomp}^S(i, \text{aux}, \alpha)$  be the procedure for computing  $f$  from  $(i, \text{aux})$  and the advice bits  $\alpha$  as asserted in [Corollary C.4](#). We now say  $f$  is “hard” if  $f$  is not in the range of  $\text{Decomp}^S$ . (Note that  $\text{Decomp}^S$  takes  $k := \log m + d - \ell + m - 1 + \rho(m-1) + \log L + 2 \leq d + (\rho+1)(m-1) + O(\log(m/\varepsilon))$  bits. As long as this is less than  $n$  bits, a hard  $f$  must exist.)

Suppose that we are given some  $f$  that is hard. We can create injection-surjection pairs between  $X_{i,\text{aux}}$  and  $Y_{i,\text{aux}}$  by brute force; this only takes deterministic  $\text{poly}(2^\ell)$  time with oracle access to  $S$ . As an example, we construct

$$Y_{i,\text{aux}} \xrightleftharpoons[G_{i,\text{aux}}]{H_{i,\text{aux}}} X_{i,\text{aux}} \dot{\cup} [\varepsilon' \cdot 2^{\ell+1}].$$

- $G_{i,\text{aux}}(v)$ : If  $v \in X_{i,\text{aux}}$  then let  $p$  be the integer such that  $v$  is the (lexicographically)  $p$ -th smallest element of  $X_{i,\text{aux}}$  (the smallest element is the 0-th); if  $v \in [\varepsilon' \cdot 2^{\ell+1}]$  then let  $p := |X_{i,\text{aux}}| + v$ . Return the  $p$ -th smallest element of  $Y_{i,\text{aux}}$ ; if  $|Y_{i,\text{aux}}| \geq p$  then return an arbitrary element (say the smallest one).

- $H_{i,\text{aux}}(v)$ : Suppose that  $v$  is the  $p$ -th smallest element of  $Y_{i,\text{aux}}$ . If  $p < |X_{i,\text{aux}}|$  then return the  $p$ -th smallest element of  $X_{i,\text{aux}}$ ; otherwise return  $p - |X_{i,\text{aux}}| \in [\varepsilon' \cdot 2^{\ell+1}]$ .
- It is straightforward to verify that  $G_{i,\text{aux}} \circ H_{i,\text{aux}}$  is the identity map and that  $G_{i,\text{aux}}$  and  $H_{i,\text{aux}}$  are computable in deterministic  $\text{poly}(2^\ell)$  time.

We can similarly construct  $X_{i,\text{aux}} \xrightarrow[G'_{i,\text{aux}}]{H'_{i,\text{aux}}} Y_{i,\text{aux}} \dot{\cup} [\varepsilon' 2^{\ell+1}]$  such that  $G'_{i,\text{aux}} \circ H'_{i,\text{aux}}$  is the identity map and  $G'_{i,\text{aux}}$  and  $H'_{i,\text{aux}}$  are computable in deterministic  $\text{poly}(2^\ell)$  time.

Now we describe the functions  $G_i, H_i, G'_i, H'_i$ .

- Let  $v$  be the input of  $G_i$ . If  $v \in V_{i-1}$  then write  $v = (z, r) = (z', r_i, \text{aux})$ ; if  $v \in [\text{diff}]$  then let  $\text{aux} := \lfloor v / (\varepsilon' 2^{\ell+1}) \rfloor$  (treated as both a number in  $[2^{m+d-\ell-1}]$  and a length- $(m+d-\ell-1)$  string) and  $v' := v - \text{aux} \cdot \varepsilon' 2^{\ell+1}$ . Assuming  $f$  is hard, we have  $v \in X_{i,\text{aux}} \dot{\cup} [\varepsilon' 2^{\ell+1}]$ . Let  $u := G_{i,\text{aux}}(v) \in Y_{i,\text{aux}}$ , write  $u = (z^u, r_i^u)$  and return  $G_i(v) := (z^u, r_i^u, \text{aux})$ .
- Let  $u \in V_i$  be the input of  $H_i$ , and write  $u := (z', r_i, \text{aux})$  where  $(z', r_i) \in Y_{i,\text{aux}}$ . We can compute  $v := H_{i,\text{aux}}(z', r_i) \in X_{i,\text{aux}} \dot{\cup} [\varepsilon' 2^{\ell+1}]$ . If  $v \in X_{i,\text{aux}}$  then we write  $v = (z^v, r_i^v)$  and return  $(z^v, r_i^v, \text{aux}) \in V_{i-1}$ ; if  $v \in [\varepsilon' 2^{\ell+1}]$  then we return  $\text{aux} \cdot \varepsilon' 2^{\ell+1} + v \in [\text{diff}]$ .
- The definitions of  $G'_i, H'_i$  are analogous.

It is easy to see that if  $f$  is indeed hard, then  $G_i \circ H_i$  is the identity map. However, if  $f$  is *not hard*, there is no guarantee that  $G_i \circ H_i$  is the identity map. Nevertheless we still gain something: Given any witness  $u \in V_i$  such that  $G_i(H_i(u)) \neq u$ , if we write  $u = (z', r_i, \text{aux})$  then we have  $|X_{i,\text{aux}}| - |Y_{i,\text{aux}}| > \varepsilon' 2^{\ell+1}$ . By [Corollary C.4](#), we can compute  $(i, \text{aux}, \alpha)$  from this witness  $u$  deterministically such that  $\text{Decomp}^S(i, \text{aux}, \alpha) = f$ , i.e., we found a *witness for the non-hardness of  $f$*  as well! In summary, let  $f$  be a purported hard function, we can *either* use  $f$  to perform approximate counting and obtain injection-surjection pairs  $(G_i, H_i)$  *or*, if  $(G_i, H_i)$  fails to be an injection-surjection pair, *exploit this failure* to compress  $f$ .

Finally, we can compose the functions  $\{G_i\}, \{H_i\}, \{G'_i\}$ , and  $\{H'_i\}$  to obtain  $G_<, H_<, G_>, H_>$ .

- Let  $v \in (S \dot{\cup} [\varepsilon M]) \times [D] = V_0 \dot{\cup} [m \cdot \text{diff}]$  be the input of  $G_<$ . For each  $i$  from 1 to  $m$ , if currently we have  $v \in V_{i-1} \dot{\cup} [\text{diff}]$ , then we update  $v \leftarrow G_i(v)$ ; otherwise  $v \in [\text{diff}, m \cdot \text{diff}]$  and we update  $v \leftarrow v - \text{diff}$ .
- Let  $v \in V_m = [\text{val}] \times [D]$  be the input of  $H_<$ . For each  $i$  from  $m$  downto 1, if currently we have  $v \in V_i$ , then we update  $v \leftarrow H_i(v)$ ; otherwise  $v$  is some number in  $[m \cdot \text{diff}]$  and we update  $v \leftarrow v + \text{diff}$ .
- The definitions of  $G_>, H_>$  are analogous.

It is easy to see that the functions

$$[\text{val}] \times [D] \xrightarrow[G_<]{H_<} (S \dot{\cup} [\varepsilon M]) \times [D]$$

satisfy the following property: given any  $w \in [\text{val}] \times [D]$  such that  $G_<(H_<(w)) \neq w$ , we can compute in deterministic  $\text{poly}(n, 2^\ell) = \text{poly}(n/\varepsilon)$  time a “compression”  $\text{Comp}^S(f, w)$  of  $f$  that decompresses to  $f$  via  $\text{Decomp}^S$ . Furthermore,  $G_<$  and  $H_<$  themselves can be computed in deterministic  $\text{poly}(n/\varepsilon)$  time. The conclusions for  $G_>$  and  $H_>$  can be proved similarly.  $\square$