

Local reductions

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Abstract

We reduce non-deterministic time $T \geq 2^n$ to a 3SAT instance ϕ of quasilinear size $|\phi| = T \cdot \log^{O(1)} T$ such that there is an explicit circuit C that on input an index i of $\log |\phi|$ bits outputs the i th clause, and each output bit of C depends on $O(1)$ input bits. The previous best result was C in NC^1 . Even in the simpler setting of polynomial size $|\phi| = \text{poly}(T)$ the previous best result was C in AC^0 .

More generally, for any time $T \geq n$ and parameter $r \leq n$ we obtain $\log_2 |\phi| = \max(\log T, n/r) + O(\log n) + O(\log \log T)$ and each output bit of C is a decision tree of depth $O(\log r)$.

As an application, we tighten Williams' connection between satisfiability algorithms and circuit lower bounds (STOC 2010; SIAM J. Comput. 2013).

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1 Introduction and our results

The efficient reduction of arbitrary non-deterministic computation to 3SAT is a fundamental result with widespread applications. For many of these, two aspects of the efficiency of the reduction are at a premium. The first is the length of the 3SAT instance. A sequence of works shows how to reduce non-deterministic time- T computation to a 3SAT instance ϕ of quasilinear size $|\phi| = \tilde{O}(T) := T \log^{O(1)} T$ [HS66, Sch78, PF79, Coo88, GS89, Rob91]. This has been extended to PCP reductions [BGH⁺05, Mie09, BCGT13, BCGT12].

The second aspect is the computational complexity of producing the 3SAT instance ϕ given a machine M , an input $x \in \{0, 1\}^n$, and a time bound $T = T(n) \geq n$. It is well-known and easy to verify that a ϕ of size $\text{poly}(T)$ is computable even by circuits from the restricted class NC^0 . More generally, Agrawal, Allender, Impagliazzo, Pitassi, and Rudich show [AAI⁺01] that such NC^0 reductions exist whenever AC^0 reductions do.

A stronger requirement on the complexity of producing ϕ is critical for many applications. The requirement may be called *clause-explicitness*. It demands that the i th clause of ϕ be computable, given $i \leq |\phi|$ and $x \in \{0, 1\}^n$, with resources $\text{poly}(|i|) = \text{poly} \log |\phi| = \text{poly} \log T$. In the case $|\phi| = \text{poly}(T)$, this is known to be possible by an unrestricted circuit D of size $\text{poly}(|i|)$. (The circuit has either random access to x , or, if $T \geq 2^n$, it may have x hardwired.) As a corollary, so-called succinct versions of NP-complete problems are complete for NEXP. Arora, Steurer, and Wigderson [ASW09] note that the circuit D may be taken from the restricted class AC^0 . They use this to argue that, unless $\text{EXP} = \text{NEXP}$, standard NP-complete graph problems cannot be solved in time $\text{poly}(2^n)$ on graphs of size 2^n that are described by AC^0 circuits of size $\text{poly}(n)$.

Interestingly, applications to unconditional complexity lower bounds rely on reductions that are clause-explicit and simultaneously optimize the length of the 3SAT instance ϕ and the complexity of the circuit D computing clauses. For example, the time-space tradeoffs for SAT need to reduce non-deterministic time T to a 3SAT instance ϕ of quasilinear size $\tilde{O}(T)$ such that the i th clause is computable in time $\text{poly}(|i|) = \text{poly} \log |\phi|$ and space $O(\log |\phi|)$, see e.g. [FLvMV05] or Van Melkebeek’s survey [vM06]. More recently, the importance of optimizing both aspects of the reduction is brought to the forefront by Williams’ approach to obtain lower bounds by satisfiability algorithms that improve over brute-force search by a super-polynomial factor [Wil13a, Wil11b, Wil11a, SW12, Wil13b]. To obtain lower bounds against a circuit class C using this technique, one needs a reduction of non-deterministic time $T = 2^n$ to a 3SAT instance of size $\tilde{O}(T)$ whose clauses are computable by a circuit D of size $\text{poly}(n)$ that belongs to the class C . For example, for the ACC^0 lower bounds [Wil11b, Wil13b] one needs to compute them in ACC^0 . However it has seemed “hard (perhaps impossible)” [Wil11b] to compute the clauses with such restricted resources.

Two workarounds have been devised [Wil11b, SW12]. Both exploit the fact that, under an assumption such as $\text{P} \subseteq \text{ACC}^0$, non-constructively there does exist such an efficient circuit computing clauses; the only problem is constructing it. They accomplish the latter by guessing-and-verifying it [Wil11b], or by brute-forcing it [SW12] (cf. [AK10]). The overhead in these arguments limits the consequences of satisfiability algorithms: before this work, for

a number of well-studied circuit classes C (discussed later) a lower bound against C did not follow from a satisfiability algorithm for circuits in C .

1.1 Our results

We show that, in fact, it is possible to reduce non-deterministic computation of time $T \geq 2^n$ to a 3SAT formula ϕ of quasilinear size $|\phi| = \tilde{O}(T)$ such that given an index of $\ell = \log |\phi|$ bits to a clause, one can compute (each bit of) the clause by looking at a constant number of bits of the index. Such maps are also known as local, NC^0 , or junta. More generally our results give a trade-off between decision-tree depth and $|\phi|$. The results apply to any time bound T , paying an inevitable loss in $|x| = n$ for T close to n .

Theorem 1 (Local reductions). *Let M be an algorithm running in time $T = T(n) \geq n$ on inputs of the form (x, y) where $|x| = n$. Given $x \in \{0, 1\}^n$ one can output a circuit $D : \{0, 1\}^\ell \rightarrow \{0, 1\}^{3v+3}$ in time $\text{poly}(n, \log T)$ mapping an index to a clause of a 3CNF ϕ in v -bit variables, for $v = \Theta(\ell)$, such that*

1. ϕ is satisfiable iff there is $y \in \{0, 1\}^T$ such that $M(x, y) = 1$, and
2. for any $r \leq n$ we can have $\ell = \max(\log T, n/r) + O(\log n) + O(\log \log T)$ and each output bit of D is a decision tree of depth $O(\log r)$.

Note that for $T = 2^{\Omega(n)}$ we get that D is in NC^0 and ϕ has size $2^\ell = T \cdot \log^{O(1)} T$, by setting $r := n/\log T$. We also point out that the only place where locality $O(\log r)$ (as opposed to $O(1)$) is needed in D is to index bits of the string x .

The previous best result was D in NC^1 [BGH⁺05]. Even in the simpler setting of $|\phi| = \text{poly}(T)$ the previous best result was D in AC^0 [ASW09].

Tighter connections between satisfiability and lower bounds. The quest for non-trivial satisfiability algorithms has seen significant progress recently, see e.g. [Wil11b, Her11, IMP12, BIS12, IPS13, CKS13]. Our results lower the bar for obtaining new circuit lower bounds from such algorithms. Previously, a lower bound for circuits of depth d and size s was implied by a satisfiability algorithm for depth $c \cdot d$ and size s^c for a constant $c > 1$ (for typical settings of s and d). With our proof it suffices to have a satisfiability algorithm for depth $d + c$ and size $c \cdot s$ for a constant c . These results can be extended and optimized for several well-studied circuit classes. In particular we obtain the following new connections.

Corollary 2. *For each of the following classes C , if the satisfiability of circuits in C can be solved in time $2^n/n^{\omega(1)}$ then there is a problem $f \in \text{E}^{\text{NP}}$ that is not solvable by circuits in C :*

- (1) linear-size circuits,
- (2) linear-size series-parallel circuits,
- (3) linear-size log-depth circuits,
- (4) quasi-polynomial-size SYM-AND circuits.

Recall that available size lower bounds for unrestricted circuits are between $3n - o(n)$ and $5n - o(n)$, depending on the basis [Blu84, LR01, IM02]. In 1977 Valiant [Val77] focused attention on classes (2) and (3). (Some missing details about series-parallel graphs are provided in [Cal08].) The class (4) contains ACC [Yao90, BT94], and can be simulated by number-on-forehead protocols with a polylogarithmic number of players and communication [HG91]. Williams [Wil11b] gives a quasilinear-time algorithm to evaluate a SYM-AND circuit on all inputs.

For class (4) one can in fact obtain $f \in \text{NE}$ using the seminal work by Impagliazzo, Kabanets, and Wigderson [IKW01] and its extension by Williams [Wil13a, Wil11b]. But to do so for classes (1)-(3), one would need a strengthening of [IKW01] to linear-size circuits, which we raise as an open problem.

It has long been known that the satisfiability of classes (1)-(3) can be linked to $k\text{SAT}$. Using Corollary 2, we can link $k\text{SAT}$ to circuit lower bounds. Only (1') in the following corollary was known [Wil13a, Theorem 6.1]. Our proof is different: we obtain (1') immediately from (1) in Corollary 2 by the Cook-Levin theorem. In the corollary, a $k\text{SAT}$ instance has n variables and $O(n)^k$ clauses.

Corollary 3. *In Items (1), (2), and (3) of Corollary 2 we can substitute, respectively, the following assumptions:*

(1') *The exponential time hypothesis (ETH) [IP01] is false; i.e., for every $\epsilon > 0$, 3SAT is in time $2^{\epsilon n}$,*

(2') *The strong exponential time hypothesis (SETH) is false [IP01]; i.e., there is $\epsilon < 1$ such that for every k , $k\text{SAT}$ is in time $2^{\epsilon n}$,*

(3') *there is $\alpha > 0$ such that $n^\alpha\text{-SAT}$ is in time $2^{n - \omega(n/\log \log n)}$.*

For context, the best algorithms for $k\text{SAT}$ run in time $2^{n(1 - O(1/k))}$ [DGH⁺02, PPSZ05].

Although Corollaries 2 and 3 are stated in terms of linear-size circuits, the proofs provide a close correspondence between the running time for satisfiability and the parameters of the circuit class. This is discussed in more detail later in this section, see “subsequent work.”

Finally, we consider the class of polynomial-size depth- d circuits of threshold gates, which may have unbounded or bounded weights. (The latter case corresponds to Majority.) Recall that anything computed by a poly-size depth- d circuit with unbounded weights can be computed by a depth $d + 1$ circuit with bounded weights [HMP⁺93, GHR92], and that it is not known if EXP^{NP} has poly-size unbounded-weight circuits of depth $d = 2$. For these classes (and others) we show that a lower bound for depth d follows from a satisfiability algorithm for depth $d + 2$.

Corollary 4. *Consider unbounded fan-in circuits consisting of threshold gates (either bounded- or unbounded-weight). Let d be an integer.*

Suppose that for every c , given a circuit of depth $d + 2$ and size n^c on n input bits one can decide its satisfiability in time $2^n/n^{\omega(1)}$.

Then NE does not have circuits of polynomial size and depth d .

A diagram of some of the classes mentioned above, and their relative power, can be found in [Vio13].

Our results have a few other consequences. For example they imply that the so-called succinct version of various NP-complete problems remain NEXP-complete even if described by an NC^0 circuit. In particular we obtain this for 3SAT and 3Coloring. Our techniques are also relevant to the notion of circuit uniformity. A standard notion of uniformity is log-space uniformity, requiring that the circuit is computable in logarithmic space or, equivalently, that given an index to a gate in the circuit one can compute its type and its children in linear space. Equivalences with various other uniformity conditions are given by Ruzzo [Ruz81], see also [Vol99]. We consider another uniformity condition which is stronger than previously considered ones in some respects. Specifically, we describe the circuit by showing how to compute children by an NC^0 circuit, i.e. a function with constant locality.

Theorem 5 (L-uniform \Leftrightarrow local-uniform). *Let $f : \{0, 1\}^* \rightarrow \{0, 1\}$ be a function computable by a family of log-space uniform polynomial-size circuits. Then f is computable by a family of polynomial-size circuits $C = \{C_n : \{0, 1\}^n \rightarrow \{0, 1\}\}_n$ such that there is Turing machine that on input n (in binary) runs in time $O(\text{poly } \log n)$ and outputs a map $D : \{0, 1\}^{O(\log n)} \rightarrow \{0, 1\}^{O(\log n)}$ such that*

- (i) *D has constant locality, i.e., every output bit of D depends on $O(1)$ input bits, and*
- (ii) *on input a label g of a gate in C_n , D outputs the type of g and labels for each child.*

Does this paper simplify the proof that NEXP is not in ACC? Recall that the proof [Wil11b] that NEXP is not in ACC uses as a black-box a result like Theorem 1 but with the requirement on the efficiency of D relaxed to polynomial-size circuits. If one instead uses as a black-box Theorem 1, one obtains an arguably more direct proof, reported for completeness in §6.

In fact, to obtain the separation of NEXP from ACC it suffices to prove a weaker version of Theorem 1 where D is, say, in AC^0 . This weaker version has a simpler proof, as explained in §1.2. Independently of our work, Kowalski and Van Melkebeek proved this AC^0 result (personal communication).

Subsequent work. The announcement of our results as (ECCC Technical Report 13-099, July 2013) contained the same results as above except it did not mention Corollary 3 and items (2) and (4) in Corollary 2. After that announcement several related works have appeared. Oliveira’s survey [Oli13] contains an alternative connection between satisfiability and circuit lower bounds, which yields a different proof of our Corollary 4 establishing a depth-2 overhead in that connection. Williams [Wil14] shows that the ability to count the number of satisfying assignments to circuits faster than brute-force search yields lower bounds against related circuits. His connection preserves the type of the gates in the input layer, a feature which is used to obtain some new lower bounds.

The work [BV14] builds on our results and is concurrent with [Wil14]. It gives a connection between derandomization and lower bounds that also preserves the type of the gates in the input layer. Thus, derandomization (or satisfiability), as opposed to counting, is sufficient for the lower bounds in [Wil14]. [BV14] also improves the depth loss of 2 in Corollary 4 to 1. Finally, they make a step in the direction we suggested of optimizing the constants in

Item (1) of Corollary 2. In combination with the standard Cook-Levin reduction to 3SAT, they obtain that if 3SAT is in deterministic time c^n for any $c < 2^{1/10} = 1.07\dots$ then E^{NP} does not have circuits of size $3n$ over the standard, full basis. Note that such a lower bound does not easily follow from diagonalization because the description length of a circuit of size $3n$ is superlinear. (Also recall the available lower bounds have the form $3n - o(n)$). The current record for solving 3SAT deterministically has $c = 1.33\dots$ [MTY11], cf. [Her11].

As a corollary to [BV14], in this revision we show that even a somewhat more modest improvement to 3SAT algorithms would imply new lower bounds for non-boolean functions with range $m = 2$ bits. Such lower bounds do not seem known for any $m = o(n)$, cf. [KMM12].

Corollary 6 (Corollary to [BV14]). *If 3SAT is in time c^n for any $c < 2^{1/7} = 1.10\dots$, then there exists a (non-Boolean) function $f : \{0, 1\}^n \rightarrow \{0, 1\}^2$ in E^{NP} such that any circuit over the full basis computing it requires at least $3n$ (non-input) gates.*

1.2 Techniques

Background: Reducing non-deterministic time T to size- $\tilde{O}(T)$ 3SAT. Our starting point is the reduction of non-deterministic time- T computation to 3SAT instances of quasilinear size $T' = \tilde{O}(T)$. The classical proof of this result [HS66, Sch78, PF79, Coo88, GS89, Rob91] hinges on the oblivious Turing machine simulation by Pippenger and Fischer [PF79]. However computing connections in the circuit induced by the oblivious Turing machine is a somewhat complicated recursive procedure, and we have not been able to use this construction for our results.

Instead, we use an alternative proof that replaces this simulation by coupling an argument due to Gurevich and Shelah [GS89] with sorting circuits. The first reference that we are aware of for the alternative proof is the survey by Van Melkebeek [vM06, §2.3.1], which uses Batchers' odd-even mergesort networks [Bat68]. This proof was rediscovered by a superset of the authors as a class project [VN12]. We now recall it.

Consider any general model of (non-deterministic) computation, such as RAM or random-access Turing machines. (One nice feature of this proof is that it directly handles models with random-access, aka direct-access, capabilities.) The proof reduces computation to the satisfiability of a circuit C . The latter is then reduced to 3SAT via the textbook reduction. Only the first reduction to circuit satisfiability is problematic and we will focus on that one here. Consider a non-deterministic time- T computation. The proof constructs a circuit of size $\tilde{O}(T)$ whose inputs are (non-deterministic guesses of) T configurations of the machine. Each configuration has size $O(\log T)$ and contains the state of the machine, all registers, and the content of the memory locations indexed by the registers. This computation is then verified in two steps. First, one verifies that every configuration C_i yields configuration C_{i+1} assuming that all bits read from memory are correct. This is a simple check of adjacent configurations. Then to verify correctness of read/write operations in memory, one sorts the configurations by memory indices, and within memory indices by timestamp. Now verification is again a simple check of adjacent configurations. The resulting circuit is outlined in Figure 1 (for a $2k$ -tape random-access Turing machine). Using a sorting network of

quasilinear size $\tilde{O}(T)$ results in a circuit of size $\tilde{O}(T)$.

Making low-space computation local. Our first new idea is a general technique that we call *spreading computation*. This shows that any circuit C whose connections can be computed in space linear in the description of a gate (i.e., space $\log |C|$) has an equivalent circuit C' of size $|C'| = \text{poly}|C|$ whose connections can be computed with constant locality. This technique is showcased in §2 in the simpler setting of Theorem 5.

The main idea in the proof is simply to let the gates of C' represent configurations of the low-space algorithm computing children in C . Then computing a child amounts to performing one step of the low-space algorithm, (each bit of) which can be done with constant locality in a standard Turing machine model. One complication with this approach is that the circuit C' has many invalid gates, i.e., gates that do not correspond to the computation of the low-space algorithm on a label of C . This is necessarily so, because constant locality is not powerful enough to even check the validity of a configuration. Conceivably, these gates could induce loops that do not correspond to computation, and make the final 3SAT instance always unsatisfiable. We avoid cycles by including a clock in the configurations, which allows us to ensure that each invalid gate leads to a sink.

We apply spreading computation to the various sub-circuits checking consistency of configurations, corresponding to the triangles in Figure 1. These sub-circuits operate on configurations of size $O(\log T)$ and have size $\text{poly} \log T$. Hence, we can tolerate the polynomial increase in their complexity given by the spreading computation technique.

There remain however tasks for which we cannot use spreading computation. One is the sorting sub-circuit. Since it has size $> T$ we cannot afford a polynomial increase. Another task is indexing adjacent configurations. We now discuss these two in turn.

Sorting. We first mention a natural approach that gets us close but not quite to our main theorem. The approach is to define an appropriate labeling of the sorting network so that its connections can be computed very efficiently. We are able to define a labeling of bit-length $t + O(\log t) = \log \tilde{O}(T)$ for comparators in the odd-even mergesort network of size $\tilde{O}(2^t)$ (and depth t^2) that sorts $T = 2^t$ elements such that given a label one can compute the labels of its children by a decision tree of depth logarithmic in the length of the label, i.e. depth $\log \log \tilde{O}(T)$. With a similar labeling we can get linear size circuits. Or we can get constant locality at the price of making the 3SAT instance of size $T^{1+\epsilon}$. The details appear in the separate work [JMV14].

To obtain constant locality we use a variant by Ben-Sasson, Chiesa, Genkin, and Tromer [BCGT13]. They replace sorting networks with routing networks based on De Bruijn graphs. We note that routing networks have been used extensively in the PCP literature starting, to our knowledge, with the work of Polishchuk and Spielman [PS94]. They have been used mostly for their algebraic properties, whereas we exploit the small locality of these networks. Specifically, the connections of these networks involve computing bit-shift, bit-xor, and addition by 1. The first two operations can easily be computed with constant locality, but the latter cannot in the standard binary representation. However, this addition by 1 is only on

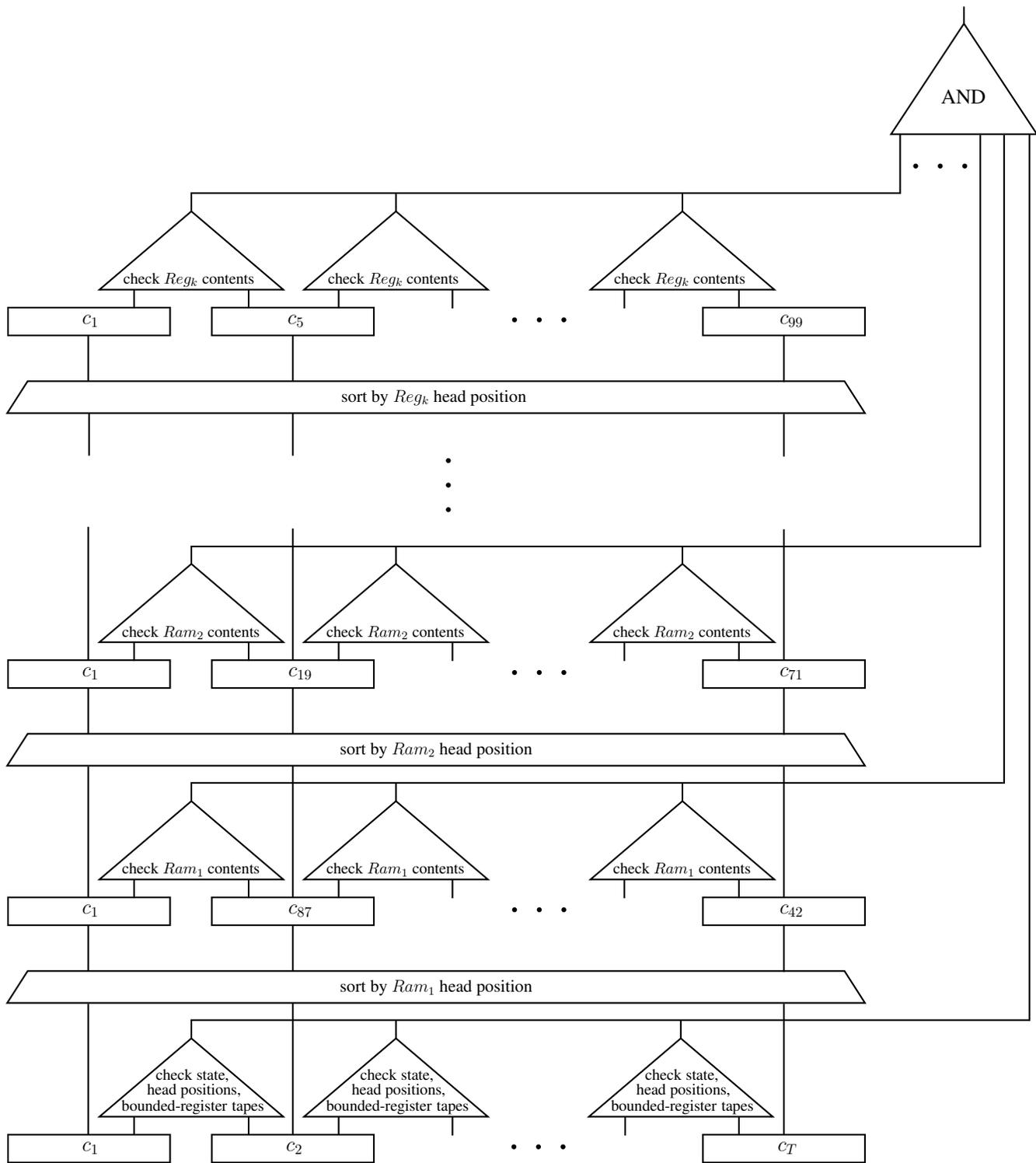


Figure 1: Each of the T configurations has size $O(\log T)$. The checking circuits have size poly $\log T$. The sorting circuits have size $\tilde{O}(T)$. k is a constant. Hence overall circuit has size $\tilde{O}(T)$.

$O(\log \log T)$ bits. Hence we can afford an alternative, redundant representation which gives us an equivalent network where all the operations can be computed with constant locality. This representation again introduces invalid labels; those are handled in a manner similar to our spreading computation technique.

Plus one. Regardless of whether we are using sorting or routing networks, another issue that comes up in all previous proofs is addition by 1 on strings of $> \log T$ bits. This is needed to index adjacent configurations C_i and C_{i+1} for the pairwise checks in Figure 1. As mentioned before, this operation cannot be performed with constant locality in the standard representation. Also, we cannot afford a redundant representation (since strings of length $c \log T$ would correspond to an overall circuit of size $> T^c$).

For context, we point out an alternative approach to compute addition by 1 with constant locality which however cannot be used because it requires an inefficient pre-processing. The approach is to use primitive polynomials over $\text{GF}(2)^{\log T}$. These are polynomials modulo which x has order $2^{\log T} - 1$. Addition by 1 can then be replaced by multiplication by x , which can be shown to be local. This is similar to *linear feedback registers*. However, it is not known how to construct such polynomials efficiently w.r.t. their degrees, see [Sho92].

To solve this problem we use routing networks in a different way from previous works. Instead of letting the network output an array C_1, C_2, \dots representing the sorted configurations, we use the network to represent the “next configuration” map $C_i \rightarrow C_{i+1}$. Viewing the network as a matrix whose first column is the input and the last column is the output, we then perform the pairwise checks on every pair of input and output configurations that are in the same row. The bits of these configurations will be in the same positions in the final label, thus circumventing addition by one.

As we mentioned earlier, for a result such as NEXP not in ACC [Wil11b] it suffices to prove a weaker version of our Theorem 1 where the reduction is computed by, say, an AC^0 circuit. For the latter, it essentially suffices to show that either the sorting network or the routing network’s connections are in that class.

Organization. §2 showcases the spreading computation technique and contains the proof of Theorem 5. In §3 we present our results on routing networks. In §4 we discuss how to fetch the bits of the input x . §5 includes the proof of our main Theorem 1. Finally, §6 we discuss connections between satisfiability algorithms and lower bounds; in particular we outline a proof of the ACC lower bound, and prove Corollaries 2, 3, and 4.

2 Spreading computation

In this section we prove Theorem 5.

Theorem 5 (L-uniform \Leftrightarrow local-uniform). *Let $f : \{0, 1\}^* \rightarrow \{0, 1\}$ be a function computable by a family of log-space uniform polynomial-size circuits. Then f is computable by a family of polynomial-size circuits $C = \{C_n : \{0, 1\}^n \rightarrow \{0, 1\}\}_n$ such that there is Turing machine*

that on input n (in binary) runs in time $O(\text{poly } \log n)$ and outputs a map $D : \{0, 1\}^{O(\log n)} \rightarrow \{0, 1\}^{O(\log n)}$ such that

- (i) D has constant locality, i.e., every output bit of D depends on $O(1)$ input bits, and
- (ii) on input a label g of a gate in C_n , D outputs the type of g and labels for each child.

We will use the following formalization of log-space uniformity: a family of polynomial-size circuits $C' = \{C'_n : \{0, 1\}^n \rightarrow \{0, 1\}\}_n$ is log-space uniform if there exists a Turing machine M that, on input $g \in \{0, 1\}^{\log |C'_n|}$ labeling a gate in C'_n , and n written in binary, uses space $O(\log n)$ and outputs the types and labels of each of g 's children. (Note that M outputs the types of g 's children rather than g 's type; the reason for this will be clear from the construction below.)

Proof. Let C' be a log-space uniform family of polynomial-size circuits and M a log-space machine computing connections in C' . We make the following simplifying assumptions without loss of generality.

- Each gate in C' has one of the following five types: And (fan-in-2), Not (fan-in-1), Input (fan-in-0), Constant-0 (fan-in-0), Constant-1 (fan-in-0).
- For all n , $|C'_n|$ is a power of 2. In particular, each $(\log |C'_n|)$ -bit string is a valid label of a gate in C'_n .
- M 's input is a label $g \in \{0, 1\}^{\log |C'_n|}$, a child-selection-bit $c \in \{0, 1\}$ that specifies which of g 's ≤ 2 children it should output, and n in binary. M terminates with $\log |C'_n|$ bits of its tape containing the child's label, and 3 bits containing the child's type.

The local-uniform family C will additionally have fan-in-1 Copy gates that compute the identity function. Gates in C are labeled by configurations of M , and we now specify these. Let $q, k, k' = O(1)$ be such that M has $2^q - 1$ states, and on input $(g, c, n) \in \{0, 1\}^{O(\log |C'_n|)}$ it uses space $\leq k \log n$ and runs in time $\leq n^{k'}$. A configuration of M is a bit-string of length $((q + 2) \cdot k + 2k') \cdot \log n$, and contains two items: the *tape* and the *timestep*.

The tape is specified with $(q + 2) \cdot k \cdot \log n$ bits. Each group of $q + 2$ bits specifies a single cell of M 's tape as follows. The first two bits specify the value of the cell, which is either 0, 1, or blank. The remaining q bits are all zero if M 's head is not on this cell, and otherwise they contain the current state of M .

The timestep is specified with $2k' \cdot \log n$ bits. In order to allow it to be incremented by a local function, we use the following representation which explicitly specifies the carry bits arising from addition. View the timestep as a sequence of pairs

$$((c_{k' \log n}, b_{k' \log n}), (c_{k' \log n - 1}, b_{k' \log n - 1}), \dots, (c_1, b_1)) \in \{0, 1\}^{2k' \log n}.$$

Then the timestep is initialized with $c_i = b_i = 0$ for all i , and to increment by 1 we simultaneously set $c_1 \leftarrow b_1$, $b_1 \leftarrow b_1 \oplus 1$, and $c_i \leftarrow b_i \wedge c_{i-1}$ and $b_i \leftarrow b_i \oplus c_{i-1}$ for all $i > 1$.

It is not difficult to see that there is a local map $\text{Upd} : \{0, 1\}^{O(\log n)} \rightarrow \{0, 1\}^{O(\log n)}$ that, on input a configuration of M , outputs the configuration that follows in a single step.

Namely **Upd** increments the timestep using the method described above, and updates each cell of the tape by looking at the $O(1)$ bits representing that cell and the two adjacent cells.

We say that a configuration is *final* iff the most-significant bit of the timestep is 1. This convention allows a local function to check if a configuration is final. Using the above method for incrementing the timestep, a final configuration is reached after $n^{k'} + k' \log n - 1$ steps. We say that a configuration is *valid* if either (a) it is the initial configuration of M on some input $(g, c) \in \{0, 1\}^{\log |C'_n| + 1}$ labeling a gate in C'_n and specifying one of its children, or (b) it is reachable from such a configuration by repeatedly applying **Upd**. (Note that **Upd** must be defined on every bit-string of the appropriate length. This includes strings that are not valid configurations, and on these it can be defined arbitrarily.)

We now describe the circuit family $C = \{C_n\}_n$ and the local map D that computes connections in these circuits, where D depends on n .

C_n has size n^u for $u := (q+2) \cdot k + 2k' = O(1)$, and each gate is labeled by an $(u \log n)$ -bit string which is parsed as a configuration of M . C_n is constructed from C'_n by introducing a chain of Copy gates between each pair of connected gates $(g_{\text{parent}}, g_{\text{child}})$ in C'_n , where the gates in this chain are labeled by configurations that encode the computation of M on input g_{parent} and with output g_{child} .

Let $g \in \{0, 1\}^{u \log n}$ be a configuration of M labeling a gate in C_n . Our convention is that if g is a final configuration then the type of g is what is specified by three bits at fixed locations on M 's tape, and if g is not a final configuration then the type is Copy. (Recall that when M terminates, the type of its output is indeed written in three bits at fixed locations.) In particular, the type of a gate can be computed from its label g by a local function.

D computes the children of its input g as follows. If g is not a final configuration, then D outputs the single child whose configuration follows in one step from g using the map **Upd** described above. If g is a final configuration, D first determines its type and then proceeds as follows. If the type is And, then D outputs two children by erasing all but the $\log |C'_n|$ bits of M 's tape corresponding to a label of a gate in C'_n , writing n , setting the timestep to 0, putting M in its initial state with the head on the leftmost cell, and finally setting one child to have $c = 0$ and one child to have $c = 1$. (Recall that c is the child-selection-bit for M .) If the type is Not, then D acts similarly but only outputs the one with $c = 0$. For any other type, g has fan-in 0 and thus D outputs no children.

Naturally, the output gate of C_n is the one labeled by the configuration consisting of the first timestep whose MSB is 1 and the tape of M containing $(g_{\text{out}}, t_{\text{out}}, n)$ where g_{out} is the unique label of C' 's output gate and t_{out} is its type. (The remainder of this configuration can be set arbitrarily.) It is clear that starting from this gate and recursively computing all children down to the fan-in-0 gates of C_n gives a circuit that computes the same function as C'_n . Call the tree computed in this way the *valid tree*.

We observe that C_n also contains gates outside of the valid tree, namely all gates whose labels do not correspond to a valid configuration. To conclude the proof, we show that the topology of these extra gates does not contain any cycles, and thus C_n is a valid circuit. By avoiding cycles, we ensure that the circuit can be converted to a constraint-satisfaction problem (i.e. 3SAT); the existence of a cycle with an odd number of Not gates would cause

the formula to be always unsatisfiable.

Consider a label g of a gate in C_n containing a configuration of M . If g is the label of a gate in the valid tree, then it is clearly not part of a cycle. If g is any other label, we consider two cases: either g is a final configuration or it is not. If g is not a final configuration, then its descendants eventually lead to a final configuration g' . (This follows because of the inclusion of the timestep in each configuration, and the fact that starting from any setting of the (c_i, b_i) bits and repeatedly applying the increment procedure will eventually yield a timestep with $\text{MSB} = 1$.) Notice that the tape in g' contains $\log |C'_n|$ bits corresponding to a valid label of a gate in C'_n . (This is because of our convention that any bit-string of that length is a valid label. An alternative solution intuitively connects the gates with $\text{MSB} = 1$ to a sink, but has other complications.) Therefore the children of g' are in the valid tree, and so g' (and likewise g) is not part of a cycle. Similarly, if g is a final configuration then its children are in the valid tree and so it is not part of a cycle. \square

3 Routing networks

In this section we show how to non-deterministically implement the sorting subcircuits. We do this in a way so that for every input sequence of configurations, at least one non-deterministic choice results in a correctly sorted output sequence. Further, each possible output sequence either is a permutation of the input or contains at least one “dummy configuration” (wlog the all-zero string). Importantly, the latter case can be detected by the configuration-checking subcircuits.

Theorem 7. *Fix $T = T(n) \geq n$. Then for all $n > 0$, there is a circuit*

$$S : (\{0, 1\}^{O(\log T)})^T \times \{0, 1\}^{O(T \log T)} \rightarrow (\{0, 1\}^{O(\log T)})^T$$

of size $T' := T \cdot \log^{O(1)} T$ and a labelling of the gates in S by strings in $\{0, 1\}^{\log T'}$ such that the following holds.

1. *There is a local map $D : \{0, 1\}^{\log T'} \times \{0, 1\} \rightarrow \{0, 1\}^{\log T'}$ such that for every label g of a gate in S , $D(g, b)$ outputs the label of one of g 's ≤ 2 children (according to b). Further, the type of each gate can be computed from its label in NC^0 . The latter NC^0 circuit is itself computable in time $\text{poly} \log T$.*
2. *Given a $(\log T + O(\log \log T))$ -bit index into S 's output, the label of the corresponding output gate can be computed in NC^0 . Further, given any input gate label, the corresponding $(\log T + O(\log \log T))$ -bit index into the input can be computed in NC^0 . These two NC^0 circuits are computable in time $\text{poly} \log T$.*
3. *For every $C = (C_1, \dots, C_T)$ and every permutation $\pi : [T] \rightarrow [T]$, there exists z such that $S(C, z) = (C_{\pi(1)}, \dots, C_{\pi(T)})$.*
4. *For every $C = (C_1, \dots, C_T)$ and every z , if $(C'_1, \dots, C'_T) := S(C, z)$ is not a permutation of the input then for some i , C'_i is the all-zero string.*

We construct this circuit S using a *routing network*.

Definition 8. Let G be a directed layered graph with ℓ columns, m rows, and edges only between subsequent columns such that each node in the first (resp. last) $\ell - 1$ columns has exactly two outgoing (resp. incoming) edges.

G is a *routing network* if for every permutation $\pi : [m] \rightarrow [m]$, there is a set of m node-disjoint paths that link the i -th node in the first column to the $\pi(i)$ -th node in the last column, for all i .

Our circuit S will be a routing network in which each node is a 2×2 switch that either direct- or cross-connects (i.e. flips) its input pair of configurations to its output pair, depending on the value of an associated control bit. This network is used to non-deterministically sort the input sequence by guessing the set of control bits. We use routing networks constructed from De Bruijn graphs as given in [BCGT13].

Definition 9. An n -dimensional De Bruijn graph DB_n is a directed layered graph with $n + 1$ columns and 2^n rows. Each node is labeled by (w, i) where $w \in \{0, 1\}^n$ specifies the row and $0 \leq i \leq n$ specifies the column. For $i < n$, each node (w, i) has outgoing edges to $(\text{sr}(w), i + 1)$ and $(\text{sr}(w) \oplus 10 \cdots 0, i + 1)$, where sr denotes cyclic right shift.

A k -tandem n -dimensional De Bruijn graph DB_n^k is a sequence of k n -dimensional De Bruijn graphs connected in tandem.

A proof of the following theorem can be found in [BCGT13].

Theorem 10. For every n , DB_n^4 is a routing network.

To use this in constructing the sorting circuit S , we must show how, given the label (w, i) of any node in DB_n^4 , to compute in NC^0 the labels of its two predecessors.

Computing the row portion of each label (corresponding to w) is trivially an NC^0 operation, as w is mapped to $\text{sl}(w)$ and $\text{sl}(w \oplus 10 \cdots 0)$ where sl denotes cyclic left shift.

For the column portion (corresponding to i), we use the encoding of integers from Theorem 5 that explicitly specifies the carry bits arising from addition. Namely, we use a $(2 \log(4n))$ -bit counter as described there, and number the columns in reverse order so that the last column is labeled by the initial value of the counter and the first column is labeled by the maximum value. This actually results in more columns than needed, specifically $4n + \log(4n)$, due to the convention that the counter reaches its maximum when the MSB becomes 1. (We use this convention here to determine when we are at the input level of the circuit.) However, note that adding more columns to DB_n^4 does not affect its rearrangeability since whatever permutation is induced by the additional columns can be accounted for by the rearrangeability of the first $4n + 1$ columns.

The next proof will introduce some dummy configurations whose need we explain now. With any routing network, one can talk about either edge-disjoint routing or node-disjoint routing. Paraphrasing [BCGT13, first par after Def A.6], a routing network with m rows can be used to route $2m$ configurations using edge-disjoint paths (where each node receives and sends two configs), or m configurations using node-disjoint paths (where each node receives

and sends one configuration). In the former every edge carries a configuration, while in the latter only half the edges between each layer carry configurations (which half depends on the permutation being routed). However, when implementing either type of routing with a boolean circuit, all edges must of course always be present and carry some data, because they correspond to wires. Thus for node-disjoint routing, half of the edges between each layer carry “dummy configurations” in our construction, and it is possible even for the dummy configurations to appear at the output of the network for certain (bad) settings of the switches. This whole issue would be avoided with edge-disjoint routing (which is arguably more natural when implementing routing networks with circuits), but we prefer to rely on existing proofs as much as possible.

Proof of Theorem 7. The circuit S is a De Bruijn graph with T rows and $4 \log T + \log(4 \log T)$ columns as described above. It routes the T configurations specified by its first input according to the set of paths specified by its second input. Each node not in the first or last column is a 2×2 switch on $O(\log T)$ -bit configurations with an associated control bit from S 's second input specifying whether to swap the configurations. Each node in the last column has a control bit that selects which of its two inputs to output. Nodes in the first column map one input to two outputs; these have no control bits, and output their input along with the all-zero string.

We label each non-input gate in S by $(t = 00, w, i, s, d)$ where $t = 00$ specifies “non-input”, $(w, i) \in \{0, 1\}^{\log T} \times \{0, 1\}^{O(\log \log T)}$ specifies a switch (i.e. a node in the De Bruijn graph), and $(s, d) \in \{0, 1\}^{O(\log \log T)} \times \{0, 1\}^{O(1)}$ specifies a gate within this switch. For the latter, we view a switch on $O(\log T)$ -bit configurations as $O(\log T)$ switches on individual bits; then s designates an $O(1)$ -sized bit switch, and d designates a gate within it.

We label each gate in S 's first input by $(t = 01, w, s)$ where $t = 01$ specifies “first input”, $w \in \{0, 1\}^{\log T}$ specifies one of the T configurations, and $s \in \{0, 1\}^{O(\log \log T)}$ specifies a bit within the configuration.

We label each gate in S 's second input by $(t = 10, w, i)$ where $t = 10$ specifies “second input” and $(w, i) \in \{0, 1\}^{\log T} \times \{0, 1\}^{O(\log \log T)}$ specifies a switch.

We take any gate with $t = 11$ to be a Constant-0 gate, one of which is used to output the all-zero string in the first column.

Naturally the labels of S 's output gates vary over w and s and have $t = 00$, $i = 0 \dots 0$, and $d =$ the output gate of a bit switch; these and the input gate labels above give Property 2. Theorem 10 guarantees that Property 3 holds for some setting of the switches, and it is straightforward to verify that Property 4 holds for any setting of the switches. We now show Property 1, namely how to compute connections in S with a local map D .

Suppose $g = (t = 00, w, i, s, d)$ is the label of a non-input gate, and let $b \in \{0, 1\}$ select one of its children. There are four possible cases: (1) the child is in the same 2×2 bit switch, (2) the child is an output gate of a preceding 2×2 bit switch, (3) the child is a bit of a configuration from S 's first input or the all-zero string, or (4) the child is a control bit from S 's second input. Since each bit switch has a fixed constant-size structure, the case can be determined by reading the $O(1)$ bits corresponding to d and the MSB of i which specifies whether g is in the first column of the De Bruijn graph.

For case (1), D updates d to specify the relevant gate within the bit switch. For case (2), D updates w and i via the procedures described above, and updates d to specify the output gate of the new bit switch. For cases (3) and (4), D updates t and either copies the relevant portions $(w, s$ or $w, i)$ from the rest of g if $t \neq 11$, or sets the rest of g to all zeros if $t = 11$.

Finally we note that as in Theorem 5, there are strings that do not encode valid labels in the manner described above, and that these do not induce any cycles in the circuit S due to the way the field i is used. \square

4 Fetching bits

In this section, we construct a local-uniform circuit that will be used to fetch the bits of the fixed string $x \in \{0, 1\}^n$ in our final construction. Moreover, we demonstrate a trade-off between the length of the labels and the locality of the map between them.

Theorem 11. *For all $x \in \{0, 1\}^n$ and for all $r \in [n]$, there is a circuit C of size 2^ℓ where $\ell = n/r + O(\log n)$, a labeling of the gates in C by strings in $\{0, 1\}^\ell$, and a map $D : \{0, 1\}^\ell \rightarrow \{0, 1\}^\ell$ each bit of which is computable by a decision tree of depth $O(\log r)$ with the following properties:*

1. *All gates in C are either fan-in-0 Constant-0 or Constant-1 gates, or fan-in-1 Copy gates. In particular, C has no input gates.*
2. *There are n output gates $\text{out}_1, \dots, \text{out}_n$, a Constant-0 gate \mathbf{g}_0 , and a Constant-1 gate \mathbf{g}_1 such that, for all $i \leq n$, repeatedly applying D to the label of out_i eventually yields the label of \mathbf{g}_{x_i} .*
3. *$\forall i \leq n$: the label of out_i can be computed in NC^0 from the binary representation of i .*
4. *Given x and r the decision trees computing D , and the NC^0 circuit in the previous item can be computed in time $\text{poly}(n)$.*

Proof. We first explain the high-level idea of the construction. Assume $r = 1$, we later extend this to the general case. For each i , the chain of labels induced by D starting from the label of out_i will encode the following process. Initialize an n -bit string $s := 10 \cdots 0$ of Hamming weight 1. Then shift s to the right $i - 1$ times, bit-wise AND it with x , and finally shift it to the left $i - 1$ times. Clearly, the leftmost bit of s at the end of this process will equal x_i . The main technical difficulty is encoding counting to i for arbitrary i while allowing connections in C to be computed locally. We achieve this using similar techniques as in the proof of Theorem 5 in Section 2, namely by performing the counting with a machine M whose configurations we store in the labels of C . We now give the details.

The label of each gate in C is parsed as a tuple (t, s, d, i, c) of length $\ell = n + O(\log n)$ as follows: t is a 2-bit string specifying the type of the gate, s is the n -bit string described above, d is a 1-bit flag specifying the direction s is currently being shifted (left or right), i is the $(\log n)$ -bit binary representation of an index into x , and c is the $O(\log n)$ -bit configuration

of a machine M that operates as follows. M has $\log n$ tape cells initialized to some binary number. It decrements the number on its tape, moves its head to the left-most cell and enters a special state q^* , and then repeats this process, terminating when its tape contains the binary representation of 1. We encode M 's $O(\log n)$ -bit configurations as in Theorem 5, in particular using the same timestep format so that checking if M has terminated can be done by reading a single bit.

The label of out_i has the following natural form. The type t is Copy, s is initialized to $10 \cdots 0$, the flag d encodes “moving right”, i is the correct binary representation, and c is the initial configuration of M on input i . Note that this can be computed from i in NC^0 .

The local map D simply advances the configuration c , and shifts s in the direction specified by d iff it sees the state q^* in M 's left-most cell. If c is a final configuration and d specifies “moving right”, then D bit-wise ANDs x to s , sets d to “moving left”, and returns M to its initial configuration on input i . If c is a final configuration and d specifies “moving left”, then D outputs the unique label of the constant gate \mathbf{g}_b where b is the left-most bit of s . (Without loss of generality, we can take this to be the label with the correct type field and all other bits set to 0.)

The correctness of this construction is immediate. Furthermore, the strings that encode invalid labels do not induce cycles in C for similar reasons as those given at the end of Theorem 5. (In fact, the presence of cycles in this component would not affect the satisfiability of our final 3SAT instance, since the only gates with non-zero fan-in have type Copy.)

We now generalize the proof to any value of r . The goal is to establish a trade-off between the label length ℓ and the locality of the map D such that at one extreme we have $\ell = n + O(\log n)$ and D of constant locality and the the other we have $\ell = O(\log n)$ and D computable by decision trees of depth $O(\log n)$.

The construction is the same as before but this time the label of a gate in C is parsed as a tuple (t, p, k, d, i, c) of length $\ell = n/r + \log r + O(\log n) = n/r + O(\log n)$, where t, d, i , and c are as before and $p \in \{0, 1\}^{n/r}$ and $k \in \{0, 1\}^{\log r}$ together represent a binary string of length n and Hamming weight 1. More precisely, consider a binary string $s \in \{0, 1\}^n$ of Hamming weight 1 partitioned into r segments each of n/r bits. Now, the position of the bit set to 1 can be determined by a segment number $k \in \{0, 1\}^{\log r}$ and a bit string $p \in \{0, 1\}^{n/r}$ of Hamming weight 1 within the segment.

The map D now *cyclically* shifts the string p in the direction indicated by d , updating k as needed. For the rest, the behavior of D remains unchanged. In particular, if c is a final configuration and d specifies “moving right”, then D bit-wise ANDs the relevant n/r -bit segment of x to p and so on. To perform one such step, D needs to read the entire k in addition to a constant number of other bits, so it can be computed by decision trees of depth $O(\log r)$. \square

5 Putting it together

We now put these pieces together to prove Theorem 1. First we modify previous proofs to obtain the following normal form for non-deterministic computation that is convenient for

our purposes, cf. §1.2.

Theorem 12. *Let M be an algorithm running in time $T = T(n) \geq n$ on inputs of the form (x, y) where $|x| = n$. Then there is a function $T' = T \log^{O(1)} T$, a constant $k = O(1)$, and k logspace-uniform circuit families C_1, \dots, C_k each of size $\log^{O(1)} T$ with oracle access to x , such that the following holds:*

For every $x \in \{0, 1\}^n$, there exists y such that $M(x, y)$ accepts in $\leq T$ steps iff there exists a tuple $(z_1, \dots, z_{T'}) \in (\{0, 1\}^{O(\log T)})^{T'}$, and k permutations $\pi_1, \dots, \pi_k : [T'] \rightarrow [T']$ such that for all $j \leq k$ and $i \leq T'$, $C_j(z_i, z_{\pi_j(i)})$ outputs 1.

We note that “oracle access to x ” means that the circuits have special gates with $\log n$ input wires that output x_i on input $i \leq n$ represented in binary. Alternatively the circuits C_i do not have oracle access to x but instead there is a separate constraint that, say, the first bit of z_i equals x_i for every $i \leq n$.

Proof sketch. Model M as a random-access Turing machine running in time T' and using indices of $O(\log T') = O(\log T)$ bits. All standard models of computation can be simulated by such machines with only a polylogarithmic factor T'/T blow-up in time. Each z_i is an $O(\log T)$ -bit configuration of M on some input (x, y) . This configuration contains the timestamp $i \leq T'$, the current state of M , the indices, and the contents of the indexed memory locations; see [VN12] for details.

The circuits and permutations are used to check that $(z_1, \dots, z_{T'})$ encodes a valid, accepting computation of $M(x, y)$. This is done in $k + 1$ phases where $k = O(1)$ is the number of tapes. First, we use C_1 to check that each configuration z_i yields z_{i+1} assuming that all bits read from memory are correct, and to check that configuration $z_{T'}$ is accepting. (For this we use the permutation $\pi_1(i) := i + 1 \pmod{T'}$.) This check verifies that the state, timestamp, and indices are updated correctly. To facilitate the subsequent checks, we assume without loss of generality that M 's first n steps are a pass over its input x . Therefore, C_1 also checks (using oracle access to x) that if the timestamp i is $\leq n$ then the first index has value i and the bit read from memory is equal to x_i .

For $j > 1$, we use C_j to verify the correctness of the read/write operations in the $(j - 1)$ -th tape. To do this, we use the permutation π_j such that for each i , z_i immediately precedes $z_{\pi_j(i)}$ in the sequence of configurations that are sorted first by the $(j - 1)$ -th index and then by timestamp. Then, C_j checks that its two configurations are correctly sorted, and that if index $j - 1$ has the same value in both then the bit read from memory in the second is consistent with the first. It also checks that the value of any location that is read for the first time is blank, except for the portion on the first tape that corresponds to the input (x, y) . (Note that C_1 already verified that the first time M reads a memory index $i \leq n$, it contains x_i . No checks is performed on the y part, corresponding to this string being existentially quantified.)

We stipulate that each C_j above outputs 0 if either of its inputs is the all-zero string, which happens if the sorting circuit does not produce a permutation of the configurations (cf. Theorem 7, part 4). Finally, we observe that all checks can be implemented by a log-space uniform family of polynomial-size circuits with oracle access to x . \square

We now prove our main theorem, restated for convenience. The high-level idea is to use §2-4 to transform the circuits from Theorem 12 into circuits whose connections are computable by small-depth decision trees, and to then apply the textbook reduction from Circuit-SAT to 3SAT.

Theorem 1 (Local reductions). *Let M be an algorithm running in time $T = T(n) \geq n$ on inputs of the form (x, y) where $|x| = n$. Given $x \in \{0, 1\}^n$ one can output a circuit $D : \{0, 1\}^\ell \rightarrow \{0, 1\}^{3v+3}$ in time $\text{poly}(n, \log T)$ mapping an index to a clause of a 3CNF ϕ in v -bit variables, for $v = \Theta(\ell)$, such that*

1. ϕ is satisfiable iff there is $y \in \{0, 1\}^T$ such that $M(x, y) = 1$, and
2. for any $r \leq n$ we can have $\ell = \max(\log T, n/r) + O(\log n) + O(\log \log T)$ and each output bit of D is a decision tree of depth $O(\log r)$.

Proof. We parse D 's input as a tuple (g, r, s) , where g is the label of a gate in some component from Theorem 12, as explained next, r is a 2-bit clause index, and s is a 1-bit control string. We specifically parse g as a pair (Region, Label) as follows. Region (hereafter, R) is an $O(1)$ -bit field specifying that Label is the label of either

- (a) a gate in a circuit that implements the i th instance of some C_j ,
- (b) a gate in a circuit that provides oracle access to x ,
- (c) a gate in a circuit that implements some π_j via a routing network, or
- (d) a gate providing a bit of some configuration z_i .

Label (hereafter, L) is a $(\max(\log T, n/r) + O(\log n) + O(\log \log T))$ -bit field whose interpretation varies based on R . For (a), we take $L = (i, j, \ell)$ where $i \leq T$ and $j \leq k$ specify $C_j(z_i, z_{\pi_j(i)})$ and $\ell \in \{0, 1\}^{O(\log \log T)}$ specifies a gate within it, where we use Theorem 5 and take C_j to be a circuit whose connections are computable in NC^0 . For (b), we take L to be a $(n/r + O(\log n))$ -bit label of the circuit from Theorem 11. For (c), we take $L = (j, \ell)$ where $j \leq k$ specifies π_j and $\ell \in \{0, 1\}^{\log T + O(\log \log T)}$ specifies a gate in the circuit from Theorem 7 implementing π_j . For (d), L is simply the $(\log T + O(\log \log T))$ -bit index of the bit.

We now describe D 's computation. First note that from Theorems 5, 7, and 11, the type of g can be computed from L in NC^0 ; call this value $\text{Type} \in \{\text{And, Not, Copy, Input, } x\text{-Oracle, Constant-0, Constant-1}\}$.

Computing g 's children. D first computes the labels of the ≤ 2 children of the gate $g = (R, L)$ as follows.

If R specifies that $L = (i, j, \ell)$ is the label of a gate in $C_j(z_i, z_{\pi_j(i)})$, D computes ℓ 's child(ren) using the NC^0 circuit given by Theorem 5. The only cases not handled by this are when $\text{Type} \in \{x\text{-Oracle, Input}\}$. When $\text{Type} = x\text{-Oracle}$, the child is the i' th output gate of the bit-fetching circuit, where i' is the lower $\log n$ bits of i ; by part 3 of Theorem 11, the label of this gate can be computed in NC^0 . When $\text{Type} = \text{Input}$, the child is either the

m th bit of z_i or the m th bit of π_j 's i th output, for some $m \leq O(\log T)$. We assume without loss of generality that m is contained in binary in a fixed position in L , and that which of the two inputs is selected can be determined by reading a single bit of L . Then, the label of the bit of z_i can be computed in NC^0 by concatenating i and m , and the label of the m th bit of π_j 's i th output can be computed by part 2 of Theorem 7.

If R specifies that L is a label in the bit-fetching circuit from Theorem 11, D computes its child using the $O(\log r)$ -depth decision trees given by that theorem.

If R specifies that $L = (j, \ell)$ is the label of a sorting circuit from Theorem 7, D computes ℓ 's child(ren) using the NC^0 circuit given by that theorem. The only case not handled by this is when ℓ labels a gate in the first input to the sorting circuit, but in this case the child is a bit of some z_i where i can be computed in NC^0 by part 2 of Theorem 7.

If $\text{Type} = \text{Input}$ and (R, L) is not one of the cases mentioned above or $\text{Type} \in \{\text{Constant-0}, \text{Constant-1}\}$, D computes no children.

Outputting the clause. When the control string $s = 0$, D outputs the clause specified by g and r in the classical reduction to 3SAT, which we review now. (Recall that r is a 2-bit clause index.) The 3SAT formula ϕ contains a variable for each gate g , including each input gate, and the clauses are constructed as follows.

If $\text{Type} = \text{And}$, we denote g 's children by g_a and g_b . Then depending on the value of r , D outputs one of the four clauses in the formula

$$(g_a \vee g_b \vee \bar{g}) \wedge (g_a \vee \bar{g}_b \vee \bar{g}) \wedge (\bar{g}_a \vee g_b \vee \bar{g}) \wedge (\bar{g}_a \vee \bar{g}_b \vee g).$$

These ensure that in any satisfying assignment, $g = g_a \wedge g_b$.

If $\text{Type} = \text{Not}$, we denote g 's child by g_a . Then depending on the value of r , D outputs one of the two clauses in the formula

$$(g \vee g_a \vee g_a) \wedge (\bar{g} \vee \bar{g}_a \vee \bar{g}_a).$$

These ensure that in any satisfying assignment, $g = \bar{g}_a$.

If $\text{Type} \in \{x\text{-Oracle}, \text{Copy}\}$ or $\text{Type} = \text{Input}$ and D computed g 's child g_a , then depending on the value of r , D outputs one of the two clauses in the formula

$$(\bar{g} \vee g_a \vee g_a) \wedge (g \vee \bar{g}_a \vee \bar{g}_a).$$

These ensure that in any satisfying assignment, $g = g_a$.

If $\text{Type} = \text{Constant-0}$, D outputs the clause $(\bar{g} \vee \bar{g} \vee \bar{g})$ which ensures that in any satisfying assignment g is false (i.e. that each Constant-0 gate outputs 0). If $\text{Type} = \text{Constant-1}$, D outputs the clause $(g \vee g \vee g)$ which ensures that in any satisfying assignment g is true (i.e. that each Constant-1 gate outputs 1).

If $\text{Type} = \text{Input}$, and D did not compute a child of g , D outputs a dummy clause $(g_{\text{dummy}} \vee g_{\text{dummy}} \vee g_{\text{dummy}})$ where g_{dummy} is a string that is distinct from all other labels g .

When the control string $s = 1$, D outputs clauses encoding the restriction that each $C_j(z_i, z_{\pi_j(i)})$ outputs 1. Namely, D parses $L = (i, j, \ell)$ as above, and outputs $(g_{i,j} \vee g_{i,j} \vee g_{i,j})$, where $g_{i,j} := (i, j, \ell^*)$ and ℓ^* is the label of C_j 's output gate, which depends only on j and $\log T$ and thus can be hardwired into D . \square

6 From satisfiability to lower bounds, tightly

In this section we first outline a proof of the ACC lower bound. We then prove Corollaries 2, 3, and 4. For simplicity throughout this section we focus on lower bounds for computing functions in the class E^{NP} . As remarked earlier, in a few cases the class can be improved to NE using [IKW01, Wil13a, Wil11b].

Theorem 13 ([Wil11b]). E^{NP} does not have polynomial-size ACC circuits.

Proof sketch. Following [Wil13a], suppose that E^{NP} has ACC circuits of size n^c and depth d for some constants c and d . Let $L \in NTime(2^n) \setminus NTime(o(2^n))$ [Coo73, SFM78, Zák83]. Consider the E^{NP} algorithm that on input $x \in \{0, 1\}^n$ and $i \leq 2^n \text{poly}(n)$ computes the 3CNF ϕ_x from Theorem 1, computes its first satisfying assignment if one exists, and outputs its i th bit. By assumption this algorithm can be computed by an ACC circuit of depth d and size n^c . By hardwiring x we obtain that for every $x \in \{0, 1\}^n$ there is a circuit C_x of the same depth and size that on input i computes that i th bit.

We contradict the assumption on L by showing how to decide it in $Ntime(o(2^n))$. Consider the algorithm that on input $x \in \{0, 1\}^n$ guesses the above circuit C_x . Then it connects three copies of C_x to the decision trees with depth $O(1)$ from Theorem 1 that on input $j \in \{0, 1\}^{n+O(\log n)}$ compute the j th clause of ϕ_x , to obtain circuit C'_x . Since the paths in a decision tree are mutually exclusive, C'_x may be obtained simply by appending an $n^{O(1)}$ -size layer of And gates to a layer of the gates of C_x , and increasing the fan-in of the latter, for a total depth of $d + 1$. Then the algorithm constructs the circuit C''_x which in addition checks if the outputs of the 3 copies of C_x do not satisfy the j th clause. The circuit C''_x is ACC, and a naive implementation yields size $n^{O(c)}$ and depth $d + 3$. Running the satisfiability algorithm in [Wil11b] on C''_x determines if ϕ_x is satisfiable, and hence if $x \in L$, in time $2^{|j|}/|j|^{\omega(1)} = 2^{n+O(\log n)}/(n + O(\log n))^{\omega(1)} = o(2^n)$. \square

Proof of Corollary 2. We reason as in the proof of Theorem 13. For (1)-(3) it is immediate to see that the circuit C''_x is in the same class as C_x . For (4) recall from [BT94] that quasipolynomial-size SYM-AND circuits are equivalent to functions of the form $f(p(x_1, \dots, x_n))$, where p is a polylog-degree polynomial with integer coefficients of quasipolynomial magnitude, and f is any boolean function. Our reduction can be implemented by polynomials of constant degree, which can be absorbed in p . There remains to negate the outputs depending on the negation bits, and to take an Or. This can be viewed as having $O(1)$ functions of the form $f_i(p_i(x_1, \dots, x_n))$ and wanting some arbitrary function of their joint output. Let M be the smallest number which is bigger than the absolute value attained by any p_i . M can be taken to be quasipolynomial. Now define the polynomial $p := \sum_i M^i p_i$. The output p encodes the outputs of the p_i , and so we conclude by applying an appropriate function f to p . \square

Proof of Corollary 3. (1') is just the Cook-Levin theorem.

(3') follows from Valiant's depth reduction [Val77], an exposition of which is given in [Vio09]. It shows how to convert any linear-size log-depth circuit into an Or of $2^{O(n/\log \log n)}$

k CNFs for $k = n^\epsilon$ for any fixed ϵ . (This transformation requires selecting $O(n/\log \log n)$ wires to be removed from the circuit so that the depth is reduced. It can be verified that these wires can be computed efficiently so that the whole transformation can be carried out in polynomial time in the output circuit; in fact an efficient co-nondeterministic procedure suffices for the argument, so one could also co-nondeterministically guess the wires and verify that the depth is reduced.) Thus, if we can determine the satisfiability of any such k CNF in time $2^{n-\omega(n/\log \log n)}$, we can determine the satisfiability of the original circuit in time $2^{O(n/\log \log n)+n-\omega(n/\log \log n)} = 2^{n-\omega(n/\log \log n)} = 2^n/n^{\omega(1)}$.

(2') follows from Valiant's depth reduction for series-parallel circuits [Val77], some missing details of which are provided by Calabro [Cal08] (see remarks following this proof). It shows how to convert any linear-size series-parallel circuit into an Or of $2^{n/d}$ k CNFs for $k = 2^{2^{O(d)}}$, for any parameter d (cf. [CDL⁺12, Thm. 3.9]). Thus similarly to (3'), if we can determine the satisfiability of any such k CNF in time $2^{\epsilon n}$ for some fixed $\epsilon < 1$, then choosing $d = 2/(1 - \epsilon) = O(1)$ we can determine the satisfiability of the original circuit in time $2^{n/d} \cdot 2^{\epsilon n} = 2^{(1+\epsilon)n/2} = 2^n/n^{\omega(1)}$. \square

Remarks on series-parallel circuits. The definition we work with is given by Calabro building on Valiant's seminal work [Val77], see the definition of "VSP" in [Cal08]. It has been noted several times that such circuits of linear size may be transformed into subexponential Or-And-Or circuits with bounded bottom fan-in, see e.g. [CDL⁺12]. However, a proof seems missing from the literature. It is not immediate to obtain this proof from Theorem 8 in [Cal08], because the statement of that theorem talks about long input-output paths, whereas for the transformation one needs to forbid any long path. With the latter the proof is completed reasoning as in [Val77, Vio09]. Nevertheless, with essentially the same proof as that of Theorem 8 in [Cal08] one can forbid any long path.

We also remark that several papers add the restriction that the series-parallel circuit be of logarithmic depth. This restriction is unnecessary.

Proof of Corollary 4. We reason as in the proof of Theorem 13, and improve the depth of C''_x to $d + 2$ as follows. The algorithm will guess instead of C_x a circuit D_x that given i and a bit b computes the i th bit mentioned above xor'ed with b . In an additional preliminary stage, the algorithm will check the consistency of D by running the satisfiability algorithm on $(D_x(i, 0) \wedge D_x(i, 1))$ and on $(\neg D_x(i, 0)) \wedge \neg D_x(i, 1)$, and reject if the output is ever 1. This circuit can be implemented in depth $d + 1$. \square

Proof sketch of Corollary 6. Fix any language $L \in \text{NTime}(2^n) \setminus \text{NTime}(o(2^n))$. Theorem 2.2 of [BV14] shows the following: given $x \in \{0, 1\}^n$, one can produce in time $\text{poly}(n)$ a map D such that $D(i)$ outputs the i -th clause in a 3CNF of size $\tilde{O}(2^n)$ that is satisfiable iff $x \in L$, and further D is computable with locality 1 after fixing some $O(\log n)$ bits of its input.

Here, we compose this with the textbook reduction from 3SAT to 3Color. Recall that this reduction has a pair of nodes for each variable and a constant-size gadget for each clause. Moreover, there are no edges between clause gadgets (see remarks following this proof). Thus we can instead produce a map D' where $D'(i)$ outputs the i -th edge in a graph of size $\tilde{O}(2^n)$

that is 3-colorable iff $x \in L$, and D' is computable with locality 1 after fixing some $O(\log n)$ bits of its input. This is done as follows. We parse a typical input to D' as an index to a clause (i.e. an input to D) plus $O(1)$ control bits specifying which edge in the clause gadget to output. We include the control bits in the $O(\log n)$ bits to be fixed. Once these are fixed, the labels of the two vertices output by D' are just projections of the control bits, the clause index, and the variables in the clause. The latter are output by D , so we can modify D to obtain D' that is 1-local after $O(\log n)$ bits are fixed.

With this modification to the proofs of lower bounds from satisfiability algorithms (e.g. Theorem 13 above), we now need only two (instead of three) copies of the circuit implementing the E^{NP} search algorithm since we have a 2CSP instance (3Color) rather than a 3CSP instance (3SAT). On the other hand, the values are no longer Boolean; in the case of 3Color, three values are possible which we encode with two bits. Now in order to derive a lower bound against circuits with $3n$ non-input gates, one needs to decide in time $2^n/n^{\omega(1)}$ the satisfiability of a circuit with $2 \cdot 3n$ non-input gates, n input gates, and $O(1)$ other gates. The Cook-Levin theorem reduces this to a 3SAT instance on $7n + O(1)$ variables, so it suffices to solve 3SAT in deterministic time c^n for $c < 2^{1/7}$. The remainder of the proof follows [BV14, Thm. 1.5]. \square

In the above proof, a crucial feature of the reduction from 3SAT (or CircuitSAT) to 3Color is that there are no edges between gadgets corresponding to different clauses (or gates). Consider instead the standard reduction from 3SAT to Independent Set, which likewise produces a constant-size gadget for each clause but which also contains edges between gadgets whose clauses have conflicting literals (i.e. u and \bar{u}). In this case it is not clear how to construct an NC^0 map D that outputs edges in the graph. This is because outputting the inter-clause edges seems to require computing, from the label of a gate g in the CircuitSAT instance, the labels of all gates that share a common input with g (such gates induce clauses with conflicting literals, cf. proof of Theorem 1).

In light of this it is interesting to compare our results with [ASW09]. There the authors define a \mathcal{C} -graph as one for which there exists a map $D \in \mathcal{C}$ such that $D(i, j)$ outputs the (i, j) -th bit of the graph's adjacency matrix. They show that if $NEXP \neq EXP$ then none of the standard NP-complete graph problems (including 3Color and Independent Set) can be solved on AC^0 -graphs in time polynomial in the size of the graph [ASW09, Thm. 5]. One can instead consider a definition that corresponds to our construction above: G is a \mathcal{C} -graph if there exists a map $D \in \mathcal{C}$ such that $\{D(i) \mid i\}$ is the edge set of G . Using this latter definition, our results imply that if $NEXP \neq EXP$ then 3Color cannot be solved on NC^0 -graphs in polynomial time. However as just discussed, it is not clear how to prove such a result for e.g. Independent Set.

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