Simulating Time with Square-Root Space

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Abstract

We show that for all functions $t(n) \geq n$, every multitape Turing machine running in time t can be simulated in space only $O(\sqrt{t \log t})$. This is a substantial improvement over Hopcroft, Paul, and Valiant's simulation of time t in $O(t/\log t)$ space from 50 years ago [FOCS 1975, JACM 1977]. Among other results, our simulation implies that bounded fan-in circuits of size s can be evaluated on any input in only $\sqrt{s} \cdot poly(\log s)$ space, and that there are explicit problems solvable in $O(n)$ space which require at least $n^{2-\varepsilon}$ time on every multitape Turing machine for all $\varepsilon > 0$, thereby making a little progress on the P versus PSPACE problem.

Our simulation reduces the problem of simulating time-bounded multitape Turing machines to a series of implicitly-defined Tree Evaluation instances with nice parameters, leveraging the remarkable space-efficient algorithm for Tree Evaluation recently found by Cook and Mertz [STOC 2024].

CCS Concepts

• **Theory of computation → Complexity classes**; *Turing machines.*

Keywords

time lower bound, space complexity, multitape Turing machine, P versus PSPACE, tree evaluation problem

1 Introduction

One of the most fundamental questions in theoretical computer science is: *how does time relate to space, in computation?* For instance, can every problem solvable in polynomial space (PSPACE) also be solved in polynomial time (P)? Although it is widely believed that P ≠ PSPACE, there has been scant progress on separating time and space over the decades [17, 20, 21, 40, 50, 51]. In particular, for general models of computation (beyond one-tape models), only time lower bounds of the form $\Omega(n \log n)$ have been reported for linear-space problems, whereas P ≠ PSPACE requires showing that

there is a linear-space problem that cannot be solved in $O(n^k)$ time for every constant $k \geq 1$.

In this paper, we make another step towards separating P from PSPACE, by showing that there are problems solvable in $O(n)$ space that cannot be solved in $n^2/\log^c n$ time for some constant $c > 0$. This is the first generic polynomial separation of time and space in a robust computational model (namely, the multitape Turing machine). The separation is accomplished by exhibiting a surprisingly space-efficient simulation of generic time-bounded algorithms. More formally, let TIME$[t(n)]$ be the class of decision problems decided by $O(t(n))$-time multitape Turing machines, and let SPACE$[s(n)]$ the class decided by $O(s(n))$-space multitape Turing machines.

THEOREM 1.1. *For every function $t(n) \geq n$,*

$$\text{TIME}[t(n)] \subseteq \text{SPACE}\left[\sqrt{t(n) \log t(n)}\right].$$

We find Theorem 1.1 to be very surprising. It appears to have been a common belief for decades that t time cannot be simulated in $t^{1-\varepsilon}$ space, for any constant $\varepsilon > 0$. For example, assuming that t time cannot be simulated in $t^{1-\varepsilon}$ space, Sipser gave a poly-time derandomization of RP [48][1] and Nisan-Wigderson gave a subexponential-time derandomization of BPP ([35, Section 3.6]).[2]

Given the power of multitape Turing machines, Theorem 1.1 has many interesting consequences. Along with the ability to evaluate generic straight-line programs of length n (over a bounded domain) in only $\tilde{O}(\sqrt{n})$ space (see Section 4.1), Theorem 1.1 immediately implies by diagonalization that there are $s(n)$-space problems that cannot be solved in $s(n)^{2-\varepsilon}$ time for all $\varepsilon > 0$: a "truly-polynomial" time lower bound.

COROLLARY 1.2. *For space constructible $s(n) \geq n$, and all $\varepsilon > 0$,* SPACE$[s(n)] \not\subset$ TIME$[s(n)^{2-\varepsilon}]$.

Similarly, if Theorem 1.1 could be extended to show for *all* $\varepsilon > 0$ that every time-$t(n)$ Turing machine can be simulated in $O(t(n)^{\varepsilon})$ space, then P ≠ PSPACE would follow (see the arguments in Section 4). We discuss this possibility at the end of the paper, in Section 5. It follows from Theorem 1.2 that any complete problem for linear space requires quadratic time to be solved. For example:

COROLLARY 1.3. *The language*

$$L = \{\langle M, x, 1^k \rangle \mid |M| \leq k \text{ and } M(x) \text{ halts in space } k\}$$

requires $n^{2-\varepsilon}$ time to decide on every multitape Turing machine, for every $\varepsilon > 0$.

Another consequence is that there are *context-sensitive languages* which need essentially n^2 time to be recognized by multitape Turing machines. This follows from the fact that NSPACE[n] (nondeterministic linear space) is equivalent to the class of context-sensitive languages [27].

Since multitape Turing machines can evaluate any circuit of size s (and fan-in two) on any given input of length $n \leq s$ in only $s \cdot \text{poly}(\log s)$ time [41], it follows that arbitrary subquadratic-size circuits can be simulated by subexponential-size branching programs.[3]

COROLLARY 1.4. *There is a universal $k \geq 1$ such that for all $s \geq n$, every bounded fan-in circuit of size s and n inputs has a branching program of size at most $2^{k\sqrt{s}\log^k s}$.*

It is an interesting question whether the simulation of Theorem 1.1 can be extended beyond multitape Turing machines, to more powerful computational models. In the full version of the paper [56], we generalize Theorem 1.1 to d-dimensional multitape Turing machines.

THEOREM 1.5. *Every decision problem solvable by a $t(n)$-time d-dimensional multitape Turing machine can be decided in*

$$O((t(n)\log t(n))^{1-1/(d+1)})$$

space (on a typical one-dimensional multitape Turing machine).

The space bound of Theorem 1.5 matches the best known space bounds for simulating time-t machines with *one d-dimensional tape* [30, 31]. See Section 2.1 for more references on prior simulations.

REMARK 1.6 (EXTENSION TO OBLIVIOUS RANDOM-ACCESS MODELS). *At the present time, we do not know how to extend Theorem 1.1 to arbitrary random-access models of computation. The main issue is that the indegree of the resulting computation graph (defined in Section 3) is so high that the computation graph cannot be stored in $O(t^{1-\varepsilon})$ memory. However, we remark that if the pattern of reads and writes of a given random-access machine model is* oblivious, *in the sense that given a step-count $i = 1, \ldots, t$ specified in $O(\log t)$ bits, the names of the registers being accessed in step i can be computed in $O(\sqrt{t})$ space, then Theorem 1.1 does apply, with only a $\text{poly}(\log t)$ extra space factor. This is because such machines can be simulated by circuits of $t \cdot \text{poly}(\log t)$ size, which can in turn be simulated efficiently by multitape Turing machines in $t \cdot \text{poly}(\log t)$ time (see Section 4.1).*

Intuition. The key idea behind Theorem 1.1 is to reduce the problem of simulating arbitrary time-bounded computations to particular instances of the TREE EVALUATION problem, defined by S. Cook, McKenzie, Wehr, Braverman, and Santhanam [9]. In this problem, one is given a complete d-ary tree of height h, where each leaf of the tree is labeled with a b-bit string, and each inner node of the tree is labeled with a function from $d \cdot b$ bits to b bits.[4] (Each function is presented as a table of $2^{d \cdot b}$ values, each of which are b bits.) Each inner node computes its value by evaluating its function on the values of its d children. The task of TREE EVALUATION is to

determine the value of the root of the tree. To make this a decision problem, we will decide whether the first bit of the root's value equals 1 or not.

The obvious depth-first algorithm for TREE EVALUATION uses $O(d \cdot b \cdot h)$ space, to store intermediate results at each level of the tree. The authors of [9] conjectured that TREE EVALUATION is not in NL, which would separate NL from P (in fact, stronger separations would hold). Recent algorithmic work has led to significant skepticism that this conjecture is true. In a line of work, J. Cook and Mertz have found surprisingly space-efficient methods for TREE EVALUATION [5–8], culminating in a marvelous algorithm using space only $O(d \cdot b + h \log(d \cdot b))$ ([8, Theorem 7]).

Utilizing the old notion of block-respecting Turing machines [20], we show how to reduce time-t computations to (implicitly defined) TREE EVALUATION instances of height $h = \Theta(t/b)$, bit-length b, and fan-in d, where b is a parameter from 1 to t that we can choose, and d is a fixed constant depending on the machine. In particular, one can generate arbitrary bits of our TREE EVALUATION instance in a space-efficient way as needed.

Very roughly speaking, each level of the tree will correspond to a "time block" of b steps, and the value of each node v of the tree will be a "block of tape" of length $\Theta(b)$ (a sequence of $\Theta(b)$ contiguous cells) from some particular tape of a k-tape Turing machine; the value of the root will contain the contents of the final tape block of the computation, including the relevant accept/reject state. The evaluation function F_v at node v will simulate the Turing machine for $\Theta(b)$ steps, using the contents of k tape blocks of length $\Theta(b)$ from previous time blocks; this F_v can be computed in $O(b)$ time and space, given the relevant contents of $O(b)$-length tape blocks from all k tapes and the state from the previous time block. (The leaves of the tree roughly correspond to strings of $\Theta(b)$ blank symbols, or a block of $\Theta(b)$ symbols from the input x.) We end up with a TREE EVALUATION instance of height $h = O(t/b)$ and fan-in $d = O(1)$, where $\Theta(b)$ steps of the Turing machine are processed at each node, and where each node is labeled with a string of about $\Theta(b)$ bits. (There are several technical details to worry over, such as the problem of knowing which tape blocks to use at each time step, but this is the high-level idea.)

Observe that, under the above parameter settings, the obvious depth-first TREE EVALUATION procedure would yield an algorithm running in $\Theta(h \cdot b) = \Theta(t)$ space. Applying the Cook-Mertz procedure, and setting $d \cdot b = h \log(d \cdot b) = \Theta(t \cdot \log(d \cdot b)/b)$ to optimize the space usage, we find $b = \Theta(\sqrt{t \log t})$ and obtain the $O(\sqrt{t \log t})$ space bound of Theorem 1.1.

Organization. Section 2 discusses preliminaries (which we do not recommend skipping, but it is short). Section 3 begins by proving a short "warm-up" simulation (Theorem 3.1) which already achieves $O(\sqrt{t}\log t)$ space and gives many of the key ideas. Section 3.2 proves Theorem 1.1, and discusses the possibility of improvement. Section 4 discusses various corollaries mentioned earlier, and Section 5 concludes with a number of new directions to consider.

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[3]Unfortunately, the reference [41] does not seem to be available online. See Section 4.1 for an alternative sketch of the argument.

[4]Our notation is slightly different from the usual setup, where there is a parameter $k = 2^b$. Here, our notation more closely follows Goldreich's exposition [15].

2 Preliminaries

We assume the reader is familiar with basic notions in time and space bounded complexity [2, 14]. There are a few pieces not covered in the usual complexity textbooks which are important for this work.

Robustness of Space Complexity. It is important to recall that the class of problems $\mathrm{SPACE}[s(n)]$ is robust under changes in the definition of the underlying machine model. For essentially any model (with sequential access versus random access, or tapes versus registers) that measures space usage by the *total number of bits needed to represent the storage*, $\mathrm{SPACE}[s(n)]$ is the same complexity class. This is part of what is known as the "invariance thesis" [49, 54]. As a consequence, we do not have to worry much about machine models when we're trying to design a space $s(n)$ algorithm and we're ignoring time complexity. This allows us to be more lax in our exposition.

Block-Respecting Turing Machines. In our main simulation (Theorem 1.1) we will utilize a construction to simplify the analysis of multitape Turing machines. The construction was originally used by Hopcroft, Paul, and Valiant [20] in their $O(t/\log t)$-space simulation of t time, and it has been used in many subsequent works to "decompose" time-bounded computations (such as [25, 26, 29, 34, 38]). A *time-$t(n)$ block-respecting multitape Turing machine with blocks of length $b(n)$* has the property that on all inputs of length n, the computation is partitioned into $O(t(n)/b(n))$ *time blocks* of length $b(n)$, while each tape is partitioned into $O(t(n)/b(n))$ contiguous *tape blocks* of length $b(n)$. The key property is that for every time block, each tape head is in *exactly one* tape block during that time block, so that tape heads can switch between tape blocks only at the end of a time block. In particular, every tape head only crosses from one tape block to another, on time steps that are integer multiples of $b(n)$. A key lemma of [20] is that every multitape Turing machine can be made block-respecting with low overhead.

LEMMA 2.1 ([20]). *For every time-constructible $b(n), t(n)$ such that $\log t(n) \leq b(n) \leq t(n)$ and every $t(n)$-time ℓ-tape Turing machine M, there is an equivalent $O(t(n))$-time block-respecting $(\ell+1)$-tape Turing machine M' with blocks of length $b(n)$.*

The Tree Evaluation Problem. As mentioned earlier, we will reduce time-t computations to the TREE EVALUATION problem. Our formulation of TREE EVALUATION will be relaxed from the original notion: we allow a tree of height *at most* h, where each inner node v of the tree has $k_v \leq d$ children for some integer $k_v \geq 2$ depending on v, and v is labeled with a function from $k_v \cdot b$ bits to b bits. As before, each leaf is labeled with a b-bit string, and we wish to determine the first bit of the root's value. Prior work on TREE EVALUATION assumed a *complete d-ary tree* where all root-to-leaf paths have length equal to h; in our setting, we allow some paths to have length than h, and some nodes to have fewer than d children. However, the algorithm of Cook and Mertz works just as well in our relaxed formulation:

THEOREM 2.2 ([8], THEOREM 7). *TREE EVALUATION on trees of bit-length b, maximum height h, and fan-in at most d, can be computed in $O(d \cdot b + h \log(d \cdot b))$ space.*

In the Appendix of the full version [56], we give an overview of how the Cook-Mertz algorithm works, and describe why it extends to our case.

2.1 More Related Work

As mentioned earlier, Hopcroft, Paul, and Valiant showed that time-t multitape Turing machines can be simulated in $O(t/\log t)$ space [20]. This simulation was later extended beyond the multitape model, yielding a more space-efficient simulation for essentially all common models of computation used in algorithms and complexity [17, 40]. Paterson and Valiant [37] showed that circuits of size s can be simulated by depth $O(s/\log s)$ circuits, implying a space-efficient simulation of circuits. Similarly, Dymond and Tompa [11] showed that time t can be simulated in alternating time $O(t/\log t)$.

For decades, a square-root space simulation of the form in Theorem 1.1 has been known for *one-tape* Turing machines: Hopcroft and Ullman [21] showed that time-t Turing machines with one read-write tape can be simulated in space $O(\sqrt{t})$. Other improvements on this simulation (e.g., improving the time of the simulation, improving the model(s) slightly) include [22, 30, 36].

Paul, Pippenger, Szemerédi, and Trotter [38] proved the separation $\mathrm{NTIME}[n] \neq \mathrm{TIME}[n]$ for multitape Turing machines. Unfortunately, their proof *only* works for (one-dimensional) multitape Turing machines, and it is infamously still open to prove $\mathrm{NTIME}[n] \neq \mathrm{TIME}[n]$ in more general models. We prove Theorem 1.5 (an extension to the d-dimensional case) to illustrate that our approach via TREE EVALUATION is more broadly applicable.

3 A More Space-Efficient Simulation of Time

In this section, we prove Theorem 1.1, showing that any multitape Turing machine M running in time t can be simulated in space $O(\sqrt{t \log t})$. We will proceed by reducing the computation of M on an input x (of length n) to an instance of TREE EVALUATION with particular parameters. (In fact, in the full proof of Theorem 1.1, we will reduce computing M on x to a series of TREE EVALUATION instances.)

One initial remark is in order. First, note that we did not specify in the statement of Theorem 1.1 that the time function $t(n)$ is *time constructible*, in that there is a Turing machine that can print the value of $t(n)$ on 1^n in $O(t(n))$ steps. This is because in our space-bounded simulation, we can simply try increasing values $t(n) = n, n+1, n+2, \ldots$, one at a time, and not worry about constructibility issues. (This trick is used in other space-bounded simulations, such as [20].)

Assume M has ℓ tapes which are infinite in one direction, and all tape heads are initially at the leftmost cell. We also assume that the input x is received on tape 1.

3.1 A Warm-up Result

Before describing the full $O(\sqrt{t \log t})$ space simulation, first we present a slightly worse algorithm which uses $O(\sqrt{t} \log t)$ space and requires $t(n) \geq n^2$, but is simpler to describe. This bound is already extremely surprising (to the author), and the simulation gives most of the key intuition as well.

THEOREM 3.1. *For every function $t(n) \geq n^2$,*

$$\text{TIME}[t(n)] \subseteq \text{SPACE}[\sqrt{t(n)} \log t(n)].$$

The proof of Theorem 3.1 will utilize the well-known *oblivious* two-tape simulation of multitape Turing machines. A multitape Turing machine M is *oblivious* if for every n, and every input x of length n, the tape head movements of M on x depend *only* on n, and not on x itself.

THEOREM 3.2 ([13, 19, 42]). *For every time-$t(n)$ multitape Turing machine M, there is an equivalent time-$T(n)$ two-tape Turing machine M' which is oblivious, with $T(n) \leq O(t(n) \log t(n))$. Furthermore, given n and $i \in [T(n)]$ specified in $O(\log t(n))$ bits, the two head positions of M' on a length-n input at time step i can be computed in $\text{poly}(\log t(n))$ time.*

Let M' be the machine obtained from Theorem 3.2. The first idea behind our simulation is to conceptually partition the computation of M' on a length-n input x into time and tape "blocks" of length $b(n)$, for a parameter $b(n) \geq \log t(n)$ to be set later. In particular, the two tapes of M' are split into *tape blocks* of $b(n)$ contiguous cells, and the $T(n)$ steps of M' on x are split into $B := B(n) = O(T(n)/b(n))$ contiguous *time blocks* of length up to $b(n)$. Observe that, for any block of $b(n)$ steps on M', and any given tape $h \in \{1, 2\}$, there are at most two tape blocks of tape h that may have been accessed during the time block (moreover, they are adjacent tape blocks on tape h). We will construct a TREE EVALUATION instance where the functions at each node of the tree evaluate a single time block, taking as input some relevant tape blocks from previous time blocks. In fact, the same time block may be recomputed many times over the entire TREE EVALUATION instance, in order to evaluate the last time block at the root of the tree.

A Computation Graph. To this end, we define a *computation graph* $G_{M',x}$ on $B + 1 = O(T(n)/b(n))$ nodes, a directed acyclic graph whose edges model the information flow from earlier time blocks in the computation to later time blocks: the reads and writes of M' and the head movements across blocks of tape. Our notion is very similar to the computation graphs defined in [20, 39]. Eventually, the computation being performed on the $(B + 1)$-node graph $G_{M',x}$ will be viewed as a TREE EVALUATION instance of height $B + 1$.

Our graph $G_{M',x}$ has a node i for each time block $i \in \{0, 1, \ldots, B\}$, and the edges will indicate which previous time block contents need to be read in order to compute the content of the tape blocks accessed during time block i. In particular, we say that all tape blocks on the two tapes are *active* during time block 0, and for $i > 0$, a tape block is *active* during time block i if the tape head visits some cell of the block during time block i. We put an edge from (i, j) in $G_{M',x}$ with $i < j$ if and only if:

- either $j = i + 1$, or
- when M' is run on input x, there is some tape block active during time block i that is not active again until time block j. That is, for some tape head h, it reads the same tape block C in both time blocks i and j, but h does not read tape block C during any time blocks $i + 1, \ldots, j - 1$. (Alternatively, if some tape block is being accessed for the first time in time block i, we have an edge $(0, i)$ to reflect the fact that all tape blocks are defined to be active in time block 0.)

Observe that each node i has indegree at most 5: one edge from $i - 1$, and at most four other edges for (at most) four active tape blocks during time block i (two active tape blocks for each of the two tapes).

The key insight behind the computation graph notion is that the information needed to simulate M' during a time block j only requires knowing the information computed in previous time blocks i, where (i, j) is an edge in $G_{M',x}$. In particular, the state and head positions of M' at the start of time block j may be obtained from the state and head positions at the end of time block $j - 1$, so we have the edge $(j - 1, j)$, and we have an edge (i, j) for each of those blocks of tape accessed during a time block i which are not accessed again until time block j.

Due to the obliviousness of M' (Theorem 3.2), we have the following claim:

CLAIM 3.3. *Given the indices of any two nodes i, j in $G_{M',x}$, we can determine if there is an edge from i to j in $\text{poly}(\log t(n))$ additional space.*

The claim follows because determining whether (i, j) is an edge just requires us to keep track of the locations of the two tape heads, from some time block i to a later time block j. By Theorem 3.2, we can calculate the two tape head locations at any point in time using only $\text{poly}(\log t(n))$ time, so we only have to use $\text{poly}(\log t(n))$ space to keep track of whether a tape block accessed during time block i is only accessed later at time block j.

The Functions at the Nodes. Now we define what is being computed at each node of $G_{M',x}$. The *content* of time block i, denoted by content(i), is defined as follows:

- content(0) is the initial configuration of M' running on the input x of length n, encoded in $n + O(1)$ bits. (Recalling we have $t(n) \geq n^2$, we will eventually set $b(n) \geq n$. Thus the initial configuration of M' on x can "fit" in one tape block.)
- For $i \in \{1, \ldots, B\}$, content(i) encodes information about the status of M' on x at the *end* of time block i: the state of M', the two tape head positions, and a list of the contents of those tape blocks accessed during time block i. As there are at most four such tape blocks which may have been accessed during time block i, content(i) can be encoded in $O(b(n) + \log t(n)) \leq O(b(n))$ bits.

Note that for every fixed $j \in [B]$, if we are given content(i) for all edges (i, j) in $G_{M',x}$, then we can compute content(j) in $O(b(n))$ time and space, by simply simulating M' for $b(n)$ steps on the tape blocks of the relevant content(i) values.

Our goal is to determine content(B), the content of the final time block, which will contain either an accept or reject state and determine the answer.

A Tree Evaluation Instance. To do this, we construct a TREE EVALUATION instance in which the root node computes content(B), its children compute content(i) for all i such that (i, B) is an edge in $G_{M',x}$, and so on; the leaves of our TREE EVALUATION instance will compute content(0), the initial configuration of M' on x. This transformation is analogous to how depth-d *Boolean* circuits of fan-in F can be modeled by formulas of depth-d and size at most $O(F^d)$, by tracing over all possible paths from the output gate of the circuit to an input gate of the circuit; see for example [24, Chapter 6].

More precisely, we define a tree $R_{M',x}$ of height at most $B+1$ and fan-in at most 5, with a root node that will evaluate to content(B). Each node v of $R_{M',x}$ is labeled by a distinct path from some node j in $G_{M',x}$ to the node B of $G_{M',x}$. Inductively, we define the labels as follows:

- the root node of $R_{G'}$ is labeled by the empty string ε (the empty path from B to itself), and
- for every node v in $R_{M',x}$ labeled by a distinct path P from j to B, and for every node i with an edge to j in $G_{M',x}$, the node v has a child w in $R_{M',x}$ labeled by the path which takes the edge (i,j) then the path P to B.

Observe that paths P of length ℓ from a node j to node B can be encoded in $O(\ell)$ bits, since the indegree of each node is at most 5. Furthermore, given such a path P encoded in this way, observe we can determine the node j at the start of P in poly($\log t$) space, by making repeated calls to the edge relation (as in Theorem 3.3).

The desired value to be computed at node v (labeled by a path from j to B) is precisely content(j). For $j = 0$, this value is just the initial configuration of M' on x, which can be produced immediately in $O(n)$ time and space. For $j > 0$, content(j) can be computed in $O(b(n))$ time and space given the values of the children of v. Since $G_{M',x}$ has at most $B + 1$ total nodes, the height of $R_{M',x}$ is at most $B + 1$. By induction, the value of the root of $R_{M',x}$ is precisely content(B).

While the tree $R_{M',x}$ has $2^{\Theta(B)} \leq 2^{\Theta(T(n)/b(n))}$ nodes, observe that for any given node v of $R_{M',x}$ (labeled by a path to B), we can easily compute the labels of the children of v in poly($\log t(n)$) space, using Theorem 3.3 to compute the edges of the graph $G_{M',x}$. Thus, it takes only poly($\log t(n)$) additional space to determine the children of any given node of $R_{M',x}$, and this space can be immediately reused once these children are determined. So without loss of generality, we may assume we have random access to the tree $R_{M',x}$, its leaves, and its functions at each node.

Finally, we call the Cook-Mertz Tree Evaluation algorithm (Theorem 2.2) in its most general form on $R_{M',x}$. Recall that the space bound of this algorithm, for trees of height at most h, fan-in at most d, computing b-bit values at each node, is

$$O(d \cdot b + h \log(d \cdot b)).$$

For us, $d = 5$, $b = b(n)$, and

$$h = O(T(n)/b(n)) \leq O(t(n) \log t(n))/b(n).$$

We only use $O(b(n))$ additional time and space for each function call to compute some content(j), and we can reuse this space for every separate call. Therefore our space bound is optimized up to constant factors, by setting $b(n)$ such that

$$b(n)^2 = \Theta(t(n) \log t(n) \cdot \log b(n)),$$

so $b(n) = \sqrt{t(n)} \cdot \log t(n)$ suffices. This completes the proof of Theorem 3.1.

3.2 The Main Result

Now we describe how to improve the bound of the space simulation, by avoiding the $t \log t$ blowup of the oblivious simulation. This will establish Theorem 1.1. The main difficulty is that without the oblivious guarantee of Theorem 3.2, we do not know how to determine the edges of computation graph $G_{M,x}$ in an efficient

way. To remedy this, we will use more space: we will enumerate over possible computation graphs G', and introduce a method for checking that $G' = G_{M',x}$ in the functions of our Tree Evaluation instance. Our graph enumeration will be performed in a particularly space-efficient way, so that if Tree Evaluation turns out to be in logspace, the simulation of this paper will yield an $O(\sqrt{t(n)})$ space bound.

As before, we start with a multitape M which runs in $t(n)$ time, and let x be an input of length n.

First, we make M block-respecting as in Theorem 2.1 with block-length $b = b(n)$ on inputs of length n, for a parameter b to be set later. The new multitape machine M' has $p := \ell + 1$ tapes, runs in time $O(t(n))$, and has $B := O(t(n)/b(n))$ time and tape blocks.[5]

The Computation Graph. We start by refining the computation graph notion from Theorem 3.1. Here, our computation graph $G_{M',x}$ is similar but not identical to that of [20] and the warm-up Theorem 3.1. Because we will allow for space bounds which are smaller than the input length $n = |x|$, we have to make several modifications to $G_{M',x}$ to fit the specifications of Tree Evaluation. We define the set of nodes in $G_{M',x}$ to be

$$S = \{(h,i), (h,0,i) \mid h \in [p], i \in [B]\}.$$

Intuitively, each $(h,i) \in [p] \times [B]$ will correspond to the content of the relevant block of tape h after time block i, while each $(h,0,i)$ will be a source node in $G_{M',x}$ corresponding to the content of the i-th block of tape h when it is accessed for the first time, *i.e.*, the *initial configuration* of the i-th block of tape h.[6] (We imagine that on each tape, the tape blocks are indexed $1, 2, \ldots$ starting from the leftmost block, with up to B tape blocks for each tape.) We think of all $(h,0,i)$ nodes as associated with "time block 0".

Each node $(h,i) \in [p] \times [B]$ is labeled with an integer $m_{(h,i)} \in \{-1,0,1\}$, indicating the tape head h movement at the end of time block i:

$$m_{(h,i)} = \begin{cases} 1 & \text{if the head } h \text{ moves one tape block to the right} \\ & \text{of the current tape block,} \\ -1 & \text{if } h \text{ moves one tape block to the left, and} \\ 0 & \text{if } h \text{ stays in the same tape block for both time} \\ & \text{blocks } i \text{ and } i+1. \end{cases}$$

Next, we describe the edges of $G_{M',x}$; there are two types. For each $h, h' \in [p]$ and $i, j \in [B]$ with $i < j$, the edge $((h',i), (h,j))$ is put in $G_{M',x}$ if either:

- $j = i + 1$, or
- while M' is running during time block j, the tape block accessed by h' during time block i is not accessed again until time block j. That is, tape head h' reads the same tape block

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[5]Strictly speaking, we do not have to make M block-respecting, but it does make aspects of the presentation a little cleaner: we do not have to reason about "active" tape blocks as we did in the warm-up (Theorem 3.1). Foreshadowing a bit, we will not use a block-respecting notion in the later extension to d-dimensional Turing machines (Theorem 1.5) and again use "active" tape blocks.

[6]A little explanation may be in order. In the warm-up Theorem 3.1, we assumed $t(n) \geq n^2$, so that the entire initial configuration of the machine on x could fit in a length-$b(n)$ block. This made the leaf nodes of our Tree Evaluation instance $R_{G'}$ particularly easy to describe. For $t(n) \ll n^2$, we may have $|x| = n \ll b(n)$, so the input x may not fit in one tape block. To accommodate this possibility and obtain a clean reduction to Tree Evaluation in the end, we define multiple source nodes in $G_{M',x}$ to account for different $b(n)$-length blocks of input x in the initial configuration of M' on x, along with $b(n)$-length blocks of all-blank tape when these blocks are accessed for the first time.

T in both time blocks i and j, but head h' does not read tape block T during any of the time blocks $i + 1, \ldots, j - 1$.

For $h, h' \in [p]$ and $i, j \in [B]$, the edge $((h', 0, i), (h, j))$ is put in $G_{M',x}$ if, while M' is running during time block j, the tape head h' accesses its i-th tape block for the first time in the computation. (For example, note that , for all h, h', $((h', 0, 1), (h, 1))$ is an edge.)

Observe that the indegree of each node $(h, j) \in [p] \times [B]$ is at most $2p$ for all $j > 0$: for all $h' \in [p]$, there is an edge from $(h', j - 1)$ to (h, j) for $j > 1$ (and from $(h', 0, 1)$ to $(h, 1)$ for $j = 1$), and there is an edge from a node labeled by h' (either of the form $(h', i_{h',j})$ or $(h', 0, i_{h',j})$) to (h, j), indicating which block of tape h' is needed to compute the block of tape h during time block j. (Note that some of these edges might be double-counted, so the indegree is at most $2p$.)

A Succinct Graph Encoding. The obvious way to store the computation graph $G_{M',x}$ uses $O(B \log B)$ bits. To save space, we will be more careful, and use additional observations on the structure of such computation graphs. (These observations are similar but not identical to those used in the separation of $\mathsf{NTIME}[n]$ and $\mathsf{TIME}[n]$, of Paul-Pippenger-Szemerédi-Trotter [38].)

Recall that each node (h, i) is labeled by a head movement $m_{(h,i)} \in \{-1, 1, 0\}$ indicating whether the tape block of head h is decremented by 1, incremented by 1, or stays the same, at the end of time block i. Our key observation is that the numbers $m_{(h,i)}$ alone already tell us the entire structure of the graph $G_{M',x}$. This immediately implies that every possible *guess* of $G_{M',x}$ can be encoded in only $O(B)$ bits: we only need a constant number of bits for each of the $O(B)$ nodes.

In particular, for an index $i \in [B]$, we define $\mathrm{block}(h, i) \in [B]$ to be the index of the tape block of tape h being accessed at the *start* of time block i. For all $h \in [p]$, we have $\mathrm{block}(h, 1) = 1$, and for $i > 1$, by definition of the $m_{(h,i)}$ we have

$$\mathrm{block}(h, i) = 1 + \sum_{j=1}^{i-1} m_{(h,j)}. \tag{1}$$

Equation (1) is true because each $m_{(h,j)}$ tells us how the index of the tape block of tape h changes at the *end* of time block j, which is the same as the tape block index at the *start* of time block $j + 1$.

For $i < j$, observe that there is an edge from (h', i) to (h, j) in $G_{M',x}$ if and only if either:

- $j = i + 1$, or
- $\mathrm{block}(h', i) = \mathrm{block}(h', j)$ and for all $k \in \{i + 1, \ldots, j - 1\}$, $\mathrm{block}(h', k) \neq \mathrm{block}(h', i)$. (The tape block accessed by h' in time block i is not accessed again until time block j.)

Furthermore, there is an edge from $(h', 0, i)$ to (h, j) in $G_{M',x}$ if and only if $i = \mathrm{block}(h', j)$ and for all $k \in \{1, \ldots, j - 1\}$, $\mathrm{block}(h', j) \neq \mathrm{block}(h', k)$. (The tape block accessed by h' in time block j was never accessed before, and its index is equal to i.)

We will use a few claims about the block function and the computation graph.

CLAIM 3.4. *Given $(h', i') \in [p] \times [B]$ and the claimed sequence $\{m_{(h,i)}\}$, $\mathrm{block}(h', i')$ can be computed in $O(\log t(n))$ extra space.*

PROOF. Given any h', i', each $\mathrm{block}(h', i')$ can be computed in logspace using (1), by maintaining a counter and streaming over the sequence $m_{(h,i)}$. □

CLAIM 3.5. *Given the indices of a pair of nodes u, v in $G_{M',x}$, and the claimed sequence $\{m_{(h,i)}\}$, we can determine if (u, v) is an edge in the encoded graph in $O(\log t(n))$ additional space.*

PROOF. We can easily check if $j = i + 1$ in logspace. By Theorem 3.4, we can compute $\mathrm{block}(h', j)$ for any h', j in logspace as well. Therefore the three possible conditions for an edge in the computation graph $G_{M',x}$ can each be checked in logspace. □

To summarize, we can encode $G_{M',x}$ in $O(B)$ bits, and given such an encoding, we can determine any desired edge (u, v) of the graph in logspace.

Values of Nodes. Similarly to our warm-up Theorem 3.1, we define contents for each of the nodes of $G_{M',x}$. For all $h \in [p]$ and $i \in [B]$, we define $\mathrm{content}(h, 0, i)$ for the source nodes $(h, 0, i)$ as follows:

- If $h > 1$, then we are reading a tape h that does not contain the input. In this case, $\mathrm{content}(h, 0, i)$ is defined to be *all-blank tape content*: $b(n)$ blanks, with the tape head at the leftmost cell of the block, and head position equal to $(i - 1) \cdot b(n)$. (Note that, assuming we start numbering tape cells at 0, $(i - 1) \cdot b(n)$ is the leftmost cell of the i-th block of tape.)
- If $h = 1$, then we may need to read portions of the input x of length n. If $i > \lceil n/b(n) \rceil$, then the i-th tape block of tape 1 does not contain any symbol of x, and $\mathrm{content}(1, 0, i)$ is defined to be all-blank tape content as above. Otherwise, if $i \leq \lceil n/b(n) \rceil$, then $\mathrm{content}(1, 0, i)$ is defined to be the relevant $b(n)$-length substring of x (possibly padded with blanks at the end) with the tape head at the leftmost cell of the block, head position equal to $(i - 1) \cdot b(n)$, and the initial state of M' included if $i = 0$.

Note that the source nodes of our $G_{M',x}$ will eventually be the leaf nodes of the TREE EVALUATION instance; in the above, we are also defining the values of those leaves.

For $h \in [p]$ and $i \in [B]$, we define $\mathrm{content}(h, i)$ of node (h, i) similarly as in Theorem 3.1: it is a string encoding the pair (h, i), the state of M' and the head position of tape h at the end of time block i, and the content of the tape block read by head h at the end of time block i. With a reasonable encoding, $\mathrm{content}(h, i)$ can be represented in $O(b(n) + \log t(n)) \leq O(b(n))$ bits, and our computation graph $G_{M',x}$ has been set up (just as in Theorem 3.1) so that given the strings $\mathrm{content}(u)$ for all nodes u with edges to (h, j), the string $\mathrm{content}(h, j)$ can be computed in $O(b(n))$ time and space.

Computation Graph Enumeration. In what follows, we enumerate over all possible $O(t(n)/b(n))$-bit choices G' of the encoding of the computation graph $G_{M',x}$ on $O(B) \leq O(t(n)/b(n))$ nodes. For each G', we construct a TREE EVALUATION instance $R_{G'}$ based on G', which will attempt to simulate M' on x assuming $G' = G_{M',x}$. We will set up $R_{G'}$ so that the following conditions hold:

- If $G' \neq G_{M',x}$, this means that at the end of some time block i, some tape head h of M' on x moves inconsistently with

the guessed label $m_{(h,i)}$ in G'. In this case, evaluating $R_{G'}$ will result in a special FAIL value at the root.

- If $G' = G_{M',x}$, then $R_{G'}$ will evaluate to content$(1, B)$ at the root, which will include either an accept or reject state at the end of the computation of M' on x. Thus we will be able to conclude decisively whether M accepts or rejects x after this call to Tree Evaluation.

Finally, if we exhaust all computation graphs G' and always receive FAIL from all Tree Evaluation calls, we then increase our guess of $t(n)$ by 1 (starting from $t(n) = n$), and restart the entire process. (Recall that we do not assume $t(n)$ is constructible.) Eventually, we will choose an appropriate $t(n)$, in which case the above enumeration of graphs G' will result in either acceptance or rejection.

The Functions At The Nodes. We now define the functions at the nodes of our Tree Evaluation instance $R_{G'}$. These functions will allow us to detect when the current graph G' we are considering has an error. We have to be a little careful here, as the Cook-Mertz algorithm is only guaranteed to produce the value of the *root* of a given tree, and not the values of any intermediate nodes along the way. (Indeed, the values of other nodes may become quite "scrambled" from evaluating a low-degree extension of the functions involved.)

For each tape $h \in [p]$ and time block $i \in [B]$, we define a *time block function* $F_{h,i}$ which attempts to simulate M' over time block i, and to output content(h, i), the content of the relevant block of tape h at the end of time block i.

First, we choose an encoding of content(h, i) strings so that there is also a special FAIL string of length $O(b(n))$, which is distinct from all valid content strings.

- The **input** to $F_{h,i}$ consists of up to $2p$ strings of length $O(b(n))$. Some strings may be $O(b(n))$-bit FAIL strings. In the case where $G' = G_{M',x}$, p of the input strings have the form content$(h', i - 1)$ (or content$(h', 0, 1)$ if $i = 1$) for all $h' \in [p]$. These content strings contain the index of the node in G' they correspond to, the state q of M' at the start of time block i, the content of the relevant tape blocks at the end of time block $i - 1$, and the head positions of all p tapes at the start of time block i, where each head position is encoded in $O(\log b(n))$ bits. When some of the tape blocks accessed in time block i were not accessed in the previous time block, there are also (up to) p other strings content$(u_1), \ldots,$ content(u_p) which contain tape block content $c_1, \ldots, c_p$ for each of the p tapes at the start of time block i.
- The **output** of $F_{h,i}$ is defined as follows. First of all, if some input string is a FAIL string, then $F_{h,i}$ immediately outputs FAIL as well. In this way, a single FAIL detection at any node will propagate to the root value of $R_{G'}$.
  Assuming no FAIL strings have been given as input, $F_{h,i}$ attempts to simulate M' for time block i, using the given content strings. While simulating, $F_{h,i}$ checks that for all $h' \in [p]$, the tape head h' moves consistently with the integer $m_{(h',i)} \in \{0, 1, -1\}$. In particular, if $m_{(h',i)} = -1$ then it checks tape head h' moves to its left-adjacent tape block at the end of time block i, if $m_{(h',i)} = 1$ then it checks h'

moves to its right-adjacent tape block, and if $m_{(h',i)} = 0$ then it checks h' remains in the same tape block. If all heads h' move consistently with the integers $m_{(h',i)}$, then the output of $F_{h,i}$ is set to be content(h, i). Otherwise, the output of $F_{h,i}$ is FAIL.

Observe that $F_{h,i}$ can be computed in $O(b(n))$ time and space, by simply simulating M' for $b(n)$ steps, starting from the contents $c_1, \ldots, c_p$ for each of the tapes, and the state and head information given. Furthermore, by setting $b'(n) = \Theta(b(n))$ appropriately, we may think of each $F_{h,i}$ as a function from an ordered collection of $2p$ separate $b'(n)$-bit strings, to a single $b'(n)$-bit string. These will be the functions at the nodes of our Tree Evaluation instance.

Construct a Tree Evaluation Instance. Observe that the depth of every G' is at most $B + 1$: for every edge (u, v) in G', the time block of u is always smaller than the time block of v, and there are $B + 1$ time blocks. For each possible computation graph G', we will construct an equivalent and implicitly-defined Tree Evaluation instance $R_{G'}$ of height at most $B + 1 \leq O(t(n)/b(n))$, such that the edge relation of the tree can be determined in small space. The idea is analogous to that described in the warm-up (Theorem 3.1); for completeness, we will be a little more formal than Theorem 3.1.

Recall that each candidate G' is defined so that each non-source node (h, i) has indegree at most $2p$. Let V be the set of all $O((2p)^{B+1})$ sequences of the form $h_1 \cdots h_\ell$ for all $\ell = 0, \ldots, B$, where each $h_i \in [2p]$, and let ε denote the empty string (also in V). The nodes of $R_{G'}$ will be indexed by sequences in V. For all $\ell = 0, \ldots, B - 1$, each node $h_1 \cdots h_\ell \in V$ has at most $2p$ children $h_1 \cdots h_\ell h_{\ell+1}$ for some $h_{\ell+1} \in [2p]$.

Each node of $R_{G'}$ is directly associated with a path from a node v to the node $(1, B)$ in the guessed graph G', as follows.

- The node $\varepsilon \in V$ corresponds to the node $(1, B)$ in G' (tape 1, in the last time block), and we associate the function $F_{1,B}$ with this node.
- Inductively assume the node $h_1 \cdots h_\ell \in V$ corresponds to some node (h, j) in G'. We associate the function $F_{h,j}$ with this node.
  For every $h' \in \{1, \ldots, p\}$, the node $h_1 \cdots h_\ell h' \in V$ corresponds to a node (h', i) (or $(h', 0, i)$) in G' with an edge to (h, j), for some i. This corresponds to the case where the tape block of tape h' accessed in time block i is accessed later in time block j (or when h' is reading tape block i for the first time in time block j).
  For every $h' \in \{p + 1, \ldots, 2p\}$, let $h'' = h' - p$, so $h'' \in [p]$. The node $h_1 \cdots h_\ell h' \in V$ corresponds to the node $(h'', j - 1)$ with an edge to (h, j) when $j > 1$, and the node $(h'', 0, 1)$ with an edge to (h, j) when $j = 1$. This corresponds to the case where the state and head position of tape h'' at the end of time block $j - 1$ is passed to the start of time block j, and to the case where the initial state and head position is passed to the start of time block 1.
  If there is an edge from $(h', 0, i)$ to (h, j) for some i, then the tape head h' has never previously visited the tape block i that is used to compute time block j. In that case, we set $h_1 \cdots h_\ell h'$ to be a *leaf node* in the tree. The value of that leaf node is set to be content$(h', 0, i)$.

Finishing up. We call Tree Evaluation on $R_{G'}$. If the current guessed G' is not equal to $G_{M',x}$, then some guessed integer $m_{(h,i)} \in \{-1, 1, 0\}$ is an incorrect value (recall that G' is specified entirely by the integers $\{m_{(h,i)}\}$). This incorrect head movement will be detected by the function $F_{h,i}$, which will then output FAIL. This FAIL value will propagate to the root value of $R_{G'}$ by construction. When $R_{G'}$ evaluates to FAIL, we move to the next possible G', encoded in $O(B)$ bits.

Assuming the current graph G' is correct, *i.e.*, $G' = G_{M',x}$, then the value of the root of $R_{G'}$ is content$(1, B)$, the output of $F_{1,B}$ on the final time block B. This value contains the correct accept/reject state of M' on x. This follows from the construction of the functions $F_{h,i}$, and can be proved formally by an induction on the nodes of G' in topological order. Therefore if our Tree Evaluation call returns some content with an accept/reject state, we can immediately return the decision.

Space Complexity. Observe that, by Theorem 3.4 and Theorem 3.5, any bits of the Tree Evaluation instance $R_{G'}$ defined above can be computed in $O(B)$ space, given the computation graph G' encoded in $O(B)$ space. In particular, given the index of a node of $R_{G'}$ of the tree as defined above (as a path from a node v to $(1, B)$ in G'), we can determine the corresponding node of G' and its children in $O(B)$ space.

Therefore, we can call the Cook-Mertz algorithm (Theorem 2.2) on this implicitly-defined instance of Tree Evaluation, using $O(B)$ space plus $O(d' \cdot b' + h' \cdot \log(d \cdot b'))$ space, where

- $b' = \Theta(b(n))$ is the bit-length of the output of our functions $F_{h,i}$,
- $d' = 2p = \Theta(1)$, the number of children of each inner node, and
- $h' = B = \Theta(t(n)/b(n))$, the maximum height of the tree.

At each node, each call to one of the functions $F_{h,i}$ requires only $O(b(n))$ space. Therefore the overall space bound is

$$O\left(b(n) + \frac{t(n)}{b(n)} \cdot \log(b(n))\right).$$

Setting $b(n) = \sqrt{t(n)\log t(n)}$ obtains the bound $O(\sqrt{t(n)\log t(n)})$. This completes the proof of Theorem 1.1.

Given that we have reduced to Tree Evaluation, it may be instructive to think about what is happening in the final algorithm, conceptually. At a high level, for our instances of Tree Evaluation, the Cook-Mertz procedure on $R_{G'}$ uses $O((t(n)/b(n)) \cdot \log b(n))$ space to specify the current node v of G' being examined (given by a path from that node v to the node $(1, B)$) as well as an element from a field of size poly$(b(n))$ for each node along that path. The algorithm also reuses $O(b(n))$ space at each node, in order to compute low-degree extensions of the function $F_{h,i}$ by interpolation over carefully chosen elements of the field. For our setting of $b(n)$, we are using equal amounts of space to store a path in the graph G' labeled with field elements, and to compute a low-degree extension of the "block evaluation" function $F_{h,i}$ at each node (with aggressive reuse of the latter space, at every level of the tree).

3.3 On Possibly Removing the Square-Root-Log Factor

We observe that, if Tree Evaluation turns out to be in LOGSPACE, then we would obtain a simulation that runs in $O(b' + t(n)/b')$ space when the number of children is upper bounded by a constant. This is due to our succinct encoding of the computation graph, which only needs $O(b')$ space to be stored. Setting $b' = \sqrt{t(n)}$, this would remove the pesky $O(\sqrt{\log t})$ factor from our space bound above:

COROLLARY 3.6. *If* Tree Evaluation *is in* LOGSPACE, *then* $\mathsf{TIME}[t(n)] \subseteq \mathsf{SPACE}[\sqrt{t(n)}]$.

There may be a path to removing the $\sqrt{\log t}$ factor that does not require solving Tree Evaluation in logspace. The simulations of time t building on Hopcroft-Paul-Valiant [11, 17, 20, 37, 40], which save a $\log t$ factor in space and alternating time, utilize strategies which seem orthogonal to our approach via Tree Evaluation. Roughly speaking, there are two kinds of strategies: a pebbling strategy on computation graphs which minimizes the total number of pebbles needed [20, 40], and a recursive composition strategy which cuts the graph into halves and performs one of two recursive approaches based on the cardinality of the cut [11, 17, 37].[7] Neither of these seems comparable to the Cook-Mertz algorithm. However, so far we have been unable to merge the Tree Evaluation approach and the other strategies. The following hypothesis seems plausible:

HYPOTHESIS 3.7. *For "reasonable" $b(n)$ and $t(n)$, time-$t(n)$ multitape computations can be space-efficiently reduced to* Tree Evaluation *instances with constant degree d, height*

$$O(t(n)/b(n))/\log(t(n)/b(n)),$$

and functions from $O(b)$-bits to b-bits at each inner node.

Results such as [11, 37] which prove $\mathsf{TIME}[t] \subseteq \mathsf{ATIME}[t/\log t]$ and that circuits of size t can be simulated in depth $O(t/\log t)$, prove that the hypothesis is actually true for $b = \Theta(1)$. If the hypothesis is also true for $b = \sqrt{t}$, then we could conclude $\mathsf{TIME}[t] \subseteq \mathsf{SPACE}[\sqrt{t}]$, by applying Cook and Mertz (Theorem 2.2).

4 Some Consequences

First, we describe some simple lower bounds that follow by diagonalization. We will use the following form of the space hierarchy theorem:

THEOREM 4.1 ([50]). *For space constructible $s'(n), s(n) \geq n$ such that $s'(n) < o(s(n))$, we have* $\mathsf{SPACE}[s(n)] \not\subseteq \mathsf{SPACE}[s'(n)]$.

Reminder of Corollary 1.2. *For space-constructible $s(n) \geq n$ and all $\varepsilon > 0$,* $\mathsf{SPACE}[s(n)] \not\subseteq \mathsf{TIME}[s(n)^{2-\varepsilon}]$.

PROOF. Assume to the contrary that

$$\mathsf{SPACE}[s(n)] \subseteq \mathsf{TIME}[s(n)^{2-\varepsilon}]$$

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[7]There is even a third strategy, based on an "overlap" argument [1].

for some $\varepsilon > 0$ and some space constructible $s(n)$. By Theorem 1.1, we have

$$\text{SPACE}[s(n)] \subseteq \text{TIME}[s(n)^{2-\varepsilon}]$$
$$\subseteq \text{SPACE}[(s(n)^{2-\varepsilon} \log s(n))^{1/2}]$$
$$\subseteq \text{SPACE}[s'(n)]$$

for a function $s'(n)$ which is $o(s(n))$. This contradicts Theorem 4.1. □

Reminder of Theorem 1.3. *The language $L = \{\langle M, x, 1^k \rangle \mid |M| \leq k$ and $M(x)$ halts in space $k\}$ requires $n^{2-\varepsilon}$ time to solve on a multi-tape Turing machine, for every $\varepsilon > 0$.*

PROOF. Suppose L can be solved in $n^{2-\varepsilon}$ time for some $\varepsilon > 0$. We show every language in SPACE$[n]$ could then be solved in time $O(n^{2-\varepsilon})$, contradicting Theorem 1.2. Let $L' \in \text{SPACE}[n]$ be decided by a Turing machine M using space cn for a constant $c \geq 1$. Given an input x to M, we call our $n^{2-\varepsilon}$ time algorithm for L on the input $\langle M, x, 1^{c|x|} \rangle$ of length $n = O(|x|)$. This takes $O(|x|^{2-\varepsilon})$ time, a contradiction. □

Observe that the same proof also shows a time lower bound of the form $n^2/\log^c n$, for a constant $c > 0$.

4.1 Subexponential Size Branching Programs for Circuits

Here, we observe that Theorem 1.1 implies that subquadratic size circuits can be simulated with subexponential size branching programs:

Reminder of Theorem 1.4. *There is a universal $k \geq 1$ such that for all $s \geq n$, every bounded fan-in circuit of size s and n inputs has a branching program of size at most $2^{k\sqrt{s}\log^k s}$.*

Recall the CIRCUIT EVALUATION problem: given the description of a Boolean circuit C of fan-in two with one output, and given an input x, does C on x evaluate to 1? We assume C is encoded in *topological order*: the gates are numbered $1, \ldots, s$, and for all $i \in [s]$, the i-th gate in the encoding only takes inputs from gates appearing earlier in the encoding. For simplicity, we further assume each gate i provides a correct list of all future gates $j_1, \ldots, j_k > i$ that will consume the output of gate i. Note that when $s(n)$ is at least the number of input bits, we can still afford an encoding of size-$s(n)$ circuits in $O(s(n) \log s(n))$ bits, carrying this extra information. An old result commonly credited to Pippenger is that CIRCUIT EVALUATION on topologically-ordered circuits can be efficiently solved on multitape Turing machines:

THEOREM 4.2 (PIPPENGER [41]). CIRCUIT EVALUATION $\in$ TIME$[n \cdot poly(\log n)]$.

The reference [41] is difficult to find, however the PhD thesis of Swamy ([52, Chapter 2, Theorem 2.1]) gives an exposition of an $O(n \cdot (\log n)^3)$ time bound.[8] Swamy describes his construction as simulating oblivious RAMs / straight-line programs; it readily applies to circuits. The high-level idea is to solve a more general problem: given the description of a circuit C and input x, we wish

to insert the output values of each gate of $C(x)$ directly into the description of C. To solve this problem on C of size s, we first recursively evaluate the circuit on the first $\lfloor s/2 \rfloor$ gates (in topological order) which sets values to all those gates. We pass over those values, and collect the outputs of all gates among the first $\lfloor s/2 \rfloor$ that will be used as inputs to the remaining $\lceil s/2 \rceil$ gates. We sort these outputs by gate index, then recursively evaluate the remaining $\lceil s/2 \rceil$ gates on x plus the list of outputs. This leads to a runtime recurrence of $T(n) \leq 2 \cdot T(n/2) + O(n \cdot (\log n)^2)$ (using the fact that $n = \Theta(s \log s)$).

Combining Theorem 4.2 and Theorem 1.1, we directly conclude that CIRCUIT EVALUATION can be solved in $\sqrt{n} \cdot \text{poly}(\log n)$ space. Now, given any circuit C of size s, we hardcode its description into the input of a multitape Turing machine using $s'(n) = \sqrt{s} \cdot \text{poly}(\log s)$ space for CIRCUIT EVALUATION. Applying the standard translation of $s'(n)$-space algorithms into branching programs of $2^{O(s'(n))}$ size (see for instance the survey [45]), Theorem 1.4 follows.

5 Discussion

We have shown that multitape Turing machines and circuits have surprisingly space-efficient evaluation algorithms, via a reduction to the TREE EVALUATION problem. Two reflective remarks come to mind.

First, we find it very interesting that TREE EVALUATION, which was originally proposed and studied in the hopes of getting a handle on LOGSPACE $\neq$ P, may turn out to be more useful for making progress on P $\neq$ PSPACE. In any case, it is clear that TREE EVALUATION is a central problem in complexity theory.

Second, we find it fortunate that the main reduction of this paper (from time-t multitape Turing machine computations to TREE EVALUATION) was found *after* the Cook-Mertz procedure was discovered. Had our reduction been found first, the community (including the author) would have likely declared the following theorem (a cheeky alternative way of presenting the main reduction of Theorem 1.1) as a "barrier" to further progress on TREE EVALUATION, and possibly discouraged work on the subject:

"**Theorem.**" Unless the 50-year-old [20] simulation TIME$[t] \subseteq$ SPACE$[t/\log t]$ can be improved, TREE EVALUATION instances of constant arity, height h, and b-bit values cannot be solved in $o(h \cdot b/\log(h \cdot b))$ space.[9]

Theorem 1.1 and its relatives open up an entirely new set of questions that did not seem possible to ask before. Here are a few tantalizing ones.

Can the simulation of Theorem 1.1 be improved to show TIME$[t] \subseteq$ SPACE$[\sqrt{t}]$? We discussed some prospects for a yes-answer in Section 3.3 (*e.g.*, showing that TREE EVALUATION is in LOGSPACE). An interesting secondary question is whether the longstanding $O(\sqrt{t})$-space simulation of *one tape* time-t Turing machines [21, 36] can be improved to $O(t^{1/2-\varepsilon})$ space, for some $\varepsilon > 0$.

Is there an $\varepsilon > 0$ such that TIME$[t] \subseteq$ ATIME$[t^{1-\varepsilon}]$? Is there a better speedup of time t, using alternating Turing machines? Recall the best-known simulation is TIME$[t] \subseteq$ ATIME$[t/\log t]$ [11]. A

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[8]Available at http://static.cs.brown.edu/research/pubs/theses/phd/1978/swamy.pdf.

[9]Here, we think of $o(h \cdot b/\log(h \cdot b))$ as shorthand for $O(h \cdot b/(f(h \cdot b) \cdot \log(h \cdot b)))$ for some unbounded function f.

yes-answer to this question would imply (for example) a super-linear time lower bound on solving quantified Boolean formulas (QBF), which is still open [29, 55]. Note that if Theorem 1.1 could be improved to $\text{TIME}[t] \subseteq \text{SPACE}[t^{1/2-\varepsilon}]$ for some $\varepsilon > 0$, then we would have $\text{TIME}[t] \subseteq \text{ATIME}[t^{1-2\varepsilon}]$.

Can time-t random-access Turing machines be simulated in space $O(t^{1-\varepsilon})$, for some $\varepsilon > 0$? As mentioned in Theorem 1.6, the answer is yes for "oblivious" models in which data access patterns can be calculated in advance. In both Theorem 1.1 and Theorem 1.5, we exploit the *locality* of low-dimensional tape storage: without that property, the indegrees of nodes in the computation graph would be rather high, and (as far as we can tell) the resulting simulation would not improve the known $O(t/\log t)$ space bounds for simulating t time in random-access models [17, 40]. Similarly to the previous question, if $\text{TIME}[t] \subseteq \text{SPACE}[t^{1/2-\varepsilon}]$ for some $\varepsilon > 0$, then the answer to the question would be yes, since for natural random-access models (e.g., log-cost RAMs), time t can be simulated by $O(t^2)$-time multitape Turing machines [42]. A similar statement holds for improving the d-dimensional simulation of Theorem 1.5 [32]. On the other hand, if the answer to the question is no, then we would separate linear time for multitape Turing machines and linear time for random-access models, another longstanding open question (see for example [16]).

Is a time-space tradeoff possible? For example, is $\text{TIME}[t] \subseteq \text{TIMESPACE}[2^{\tilde{O}(t^\varepsilon)}, \tilde{O}(t^{1-\varepsilon})]$, for all $\varepsilon > 0$? The Cook-Mertz procedure needs to compute a low-degree extension of the function at each node, which is time-consuming: for time blocks of b steps, it takes $2^{\Theta(b)}$ time to compute the low-degree extension at a given point. If low-degree extensions of time-t computations could be computed more time-efficiently, then such a time-space tradeoff may be possible. Note that if the *multilinear* extension of a given CNF on n variables and m clauses could be evaluated over a large field in $1.999^n \cdot 2^{o(m)}$ time, then the Strong Exponential Time Hypothesis [4, 23] would be false: the multilinear extension is the identically-zero polynomial if and only if the CNF is unsatisfiable, so one could use DeMillo–Lipton–Schwartz–Zippel [10] to test for unsatisfiability. However, this observation does not apparently rule out the possibility of evaluating low-degree but non-multilinear extensions efficiently.

Can the simulation be applied recursively, to show that $\text{TIME}[t] \subseteq \text{SPACE}[t^\varepsilon]$ for all $\varepsilon > 0$? Note that a yes-answer would imply P $\neq$ PSPACE. At first glance, a recursive extension of Theorem 1.1 seems natural: we decompose a time-t computation into $O(t/b)$ blocks, each of which are time-b computations. (This property *was* successfully exploited recursively in [29], for example, to show some weak lower bounds on QBF.) However, we cannot directly apply recursion to time blocks, because in the Cook-Mertz procedure, the task at each function evaluation is not just to simulate for b steps, but to compute a low-degree extension of the function (as noted in the previous question). If low-degree extensions of time-t computations can be computed in small space, then there is a possibility of recursion. However, given the discussion on the previous question, there is reason to think this will be difficult.

Is there a barrier to further progress? Perhaps lower bounds for the Node-Named Jumping Automata on Graphs (NNJAG) model

(a popular model for restricted space lower bounds) [12, 43, 44] could demonstrate a barrier. Many complex algorithms such as Reingold's [46] can be simulated in the NNJAG model [33]; does the Cook-Mertz algorithm have this property as well? We believe the answer is probably no: NNJAG is fundamentally a node-pebbling model, and the Cook-Mertz procedure definitely breaks space lower bounds for pebbling DAGs and trees [9, 28]. Pebbling lower bounds were a major bottleneck to improving [20].

While Theorem 1.1 and Theorem 3.1 are non-relativizing (see for example [18]), the simulations do permit a *restricted* form of relativization, as do all prior simulations of time in smaller space. Define $\text{TIME-LENGTH}^A[t(n), \ell(n)]$ to be the class of problems solvable in $O(t(n))$ time with queries to the oracle A, where all oracle queries are restricted to have length at most $\ell(n)$. Similarly define $\text{SPACE-LENGTH}^A[s(n), \ell(n)]$. We observe the following extension of Theorem 3.1:

Theorem 5.1. *For every oracle A and $t(n) \geq n$,*
$$\text{TIME-LENGTH}^A[t(n), \sqrt{t(n)} \log t(n)]$$
$$\subseteq \text{SPACE-LENGTH}^A[\sqrt{t(n)} \log t(n), \sqrt{t(n)} \log t(n)].$$

The theorem follows because each oracle query can be arranged to be written in a single tape block of length $O(\sqrt{t(n)} \log t(n))$, and the Cook-Mertz procedure treats the evaluation functions as *black boxes*. Thus each evaluation function $F_{h,i}$ can simply call the oracle A as needed. (Tretkoff [53] made a similar observation for the simulation of $\text{TIME}[t]$ in $\Sigma_2\text{TIME}[o(t)]$, of Paul-Pippenger-Szemerédi-Trotter [38]. Such a length-restricted oracle model was also studied in [3].) Is there a barrier to improving such (restricted) relativizing results to obtain P $\neq$ PSPACE? This seems related to the fact that Cai and Watanabe [3] were unable to collapse PSPACE to P with "random access to advice" (length-restricted access to oracles).

Acknowledgments

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