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NL = UL

William M. Hoza
Department of Computer Science
The University of Chicago
williamhoza@uchicago.edu

Abstract

We present an explicit weight assignment generator that uses a seed of length $O(\log(wn))$ to assign a polynomially-bounded integer weight to each vertex of any simple width-w length-n layered digraph. For each such digraph, there is at least one seed such that the weight function is min-isolating, i.e., the minimum-weight path from s to t is unique for every s, t such that t is reachable from s. The generator is computable using $O(\log(wn))$ bits of space. Thanks to work by Reinhardt and Allender (SICOMP 2000), it immediately follows that $\mathsf{NL} = \mathsf{UL}$, i.e., every nondeterministic log-space Turing machine can be simulated by an unambiguous log-space Turing machine. The construction and analysis of the min-isolating weight function are remarkably simple.

1 Introduction

We say that a nondeterministic Turing machine is *unambiguous* if, for every input, the number of accepting computation paths is either zero or one. Let UL be the set of languages that can be decided by unambiguous log-space Turing machines. Trivially, $\mathsf{UL} \subseteq \mathsf{NL}$. It has been commonly conjectured that the two complexity classes are equal. In this paper, we unconditionally prove that the conjecture is correct.

Theorem 1.1. $\mathsf{NL} = \mathsf{UL}$.

1.1 Summary of prior work

Let us attempt to briefly summarize the large body of prior work on the NL vs. UL problem. The class UL was introduced by Buntrock, Jenner, Lange, and Rossmanith [BJLR91] and Àlvarez and Jenner [AJ93]. Arguably, the first indication that we should expect something like $\mathsf{NL} = \mathsf{UL}$ to hold came from the work of Gál and Wigderson, who proved $\mathsf{NL} \subseteq \bigoplus \mathsf{L}/\text{poly}$ [Wig94; GW96]. Reinhardt and Allender improved the containment to $\mathsf{NL} \subseteq \mathsf{UL}/\text{poly}$ using a beautiful inductive counting argument [RA00]. (The class UL is trivially contained in $\bigoplus \mathsf{L}$.) Almost all subsequent work on the NL vs. UL problem, including the present paper, builds on the techniques in Reinhardt and Allender's seminal paper [RA00].

Allender, Reinhardt, and Zhou subsequently proved $\mathsf{NL} = \mathsf{UL}$ assuming plausible circuit lower bounds [ARZ99]; Li, Pyne, and Tell proved it under a milder hardness assumption [LPT24]. Unconditionally, Van Melkebeek and Prakriya proved that every language in NL can be decided by an unambiguous Turing machine using $O(\log^{3/2} n)$ bits of space and polynomial time [vMP19]; Kallampally and Tewari independently achieved space $O(\log^2 n)$ and polynomial time [KT16]. The proof of Theorem 1.1 uses some of the ideas from Van Melkebeek and Prakriya's work [vMP19].

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Many prior works have designed unambiguous log-space algorithms for specific, important problems in NL, such as reachability in planar digraphs [ADR05; ABCDR09; BTV09; KV10; PTV12; TV12; DKTV12; AGGT16; GST19; DKMTVZ20; DGJMST21; CGT26].

Finally, Applebaum very recently proved $\mathsf{NL} \subseteq \bigoplus \mathsf{L}$ [App26], using techniques from Chatterjee, Ghosh, Gurjar, Raj, and Thierauf's recent breakthrough on the bipartite perfect matching problem [CGGRT26]. More generally, Applebaum showed $\mathsf{NL} \subseteq \mathsf{Mod}_p\mathsf{L}$ for every prime p [App26]. The class UL is trivially contained in $\mathsf{Mod}_p\mathsf{L}$, so Theorem 1.1 is an improvement of Applebaum's result [App26].

1.2 Proof method: Min-isolating weight functions

The proof of Theorem 1.1 uses the notion of a min-isolating weight function.

Definition 1.2 (Min-isolating weight function)**.** Let $G = (V, E)$ be a digraph and let $\rho\colon V \to \mathbb{N}$.[1] We consider the weight of a path with respect to ρ to be the sum of the weights of the internal vertices of the path. We say that ρ is *min-isolating* for G if, for every pair of vertices $u, v \in V$ such that v is reachable from u, there is a unique path from u to v with minimum weight with respect to ρ.

The generic Isolation Lemma of Mulmuley, Vazirani, and Vazirani [MVV87] implies that a random polynomially-bounded weight function is min-isolating for G with high probability. The key contribution of this paper is a derandomized isolation lemma for the specific case of isolating minimum-weight paths in layered digraphs.

Theorem 1.3 (An explicit min-isolating weight assignment generator for layered digraphs)**.** *For every $w, n \in \mathbb{N}$, there exists an explicit "weight assignment generator"*

$$\rho\colon \{0,1\}^{\ell} \times ([w] \times \{0, 1, \ldots, n\}) \to \mathbb{N}$$

with the following properties.

- *For every simple width-w length-n layered digraph G,*[2] *there exists a seed $x \in \{0,1\}^{\ell}$ such that the weight function $\rho_x(v) := \rho(x, v)$ is min-isolating for G.*
- *The seed length is $\ell = O(\log(wn))$, the output $\rho(x, v)$ can be computed using $O(\log(wn))$ bits of space given x and v, and the weights have magnitude $\rho(x, v) \leq \mathrm{poly}(wn)$.*

The notion of a "weight assignment generator" was introduced by Van Melkebeek and Prakriya, who gave a construction that uses a seed of length $O(\log(wn) \cdot \sqrt{\log n})$ and produces weights of magnitude $2^{O(\log(wn)\cdot\sqrt{\log n})}$ [vMP19]. The notion is also implicit in earlier work, such as Reinhardt and Allender's proof that $\mathsf{NL} \subseteq \mathsf{UL}/\mathrm{poly}$. The proof of Theorem 1.3 is remarkably simple.

Given Theorem 1.3 and Reinhardt and Allender's results [RA00], the conclusion $\mathsf{NL} = \mathsf{UL}$ is straightforward:

- It is an exercise to show that reachability in layered digraphs is NL-complete.

[1] One can more generally consider weights on the edges of the graph, but vertex weights are sufficient for our purposes.

[2] I.e., the vertex set is $[w] \times \{0, 1, \ldots, n\}$, and every edge has the form $((a, i-1), (b, i))$ for some $a, b \in [w]$ and $i \in [n]$.

- Reinhardt and Allender designed unambiguous algorithms to check whether a given weight function $\rho\colon V \to \mathbb{N}$ is min-isolating for a given digraph $G = (V, E)$, as well as to decide reachability in G under the assumption that ρ is min-isolating [RA00]. Their algorithms use $O(\log |V| + \log(M+1))$ bits of space, where $M = \max_v \rho(v)$. Furthermore, their algorithms are "$\mathsf{UL} \cap \mathsf{coUL}$" algorithms, i.e., there is a single computation path that outputs the correct answer (yes or no), and all other computation paths output $\perp$.
- Therefore, to decide reachability in layered digraphs, we can try all seeds $x \in \{0,1\}^\ell$. For each seed, we use Reinhardt and Allender's algorithm to check whether ρ_x is min-isolating for G [RA00]. If it is, we use ρ_x and Reinhardt and Allender's other algorithm to decide reachability in G [RA00].

The remainder of this paper consists of the proof of Theorem 1.3.

2 Min-isolating weights for layered digraphs

2.1 Construction

Let $C\colon [w] \to \{0,1\}^\ell$ be an explicit error correcting code with minimum distance d. Eventually, we will choose a large enough $d = \Theta(\log(wn))$. We can achieve such a minimum distance while also ensuring that $\ell = O(\log(wn))$ and that $C(a)$ can be computed using $O(\log(wn))$ bits of space. For example, we could use Justesen codes [Jus72].

Let V be the vertex set, $V = [w] \times \{0, 1, \ldots, n\}$. For convenience, extend the error correcting code C to the larger domain V by the rule $C((a,i)) = C(a)$. For each seed $x \in \{0,1\}^\ell$, we define a weight function $\rho_x\colon V \to \mathbb{N}$ by the following formula. If a vertex v is in layer $i \in [n]$, then

$$\rho_x(v) = \sum_{j=1}^{\ell} 6^{\nu_2(i)+\ell-j} \cdot C(v)_j \cdot x_j, \tag{1}$$

where $\nu_2(i)$ is the 2-adic valuation of i, i.e., $\nu_2(i) := \max\{r : 2^r \text{ divides } i\}$. (There is nothing special about the number 6; any large enough constant would work in its place.) If v is in layer zero, then $\rho_x(v) = 0$. Clearly, this generator can be computed in space $O(\log(wn))$, and it outputs integer weights that are at most $\mathrm{poly}(nw)$.

The factor of $6^{\nu_2(i)}$ in Eq. (1) is reminiscent of Van Melkebeek and Prakriya's constructions [vMP19], which also use larger magnitude weights in layers where $\nu_2(i)$ is large.

2.2 Analysis

We require the following elementary fact about the 2-adic valuation function.

Lemma 2.1. *Let I be a finite, nonempty, interval subset of $\mathbb{Z}_{>0}$. Let $M = \max_{i \in I} \nu_2(i)$. Then for every $\Delta \geq 0$, there are at most 2^Δ values $i \in I$ such that $\nu_2(i) = M - \Delta$. In particular, there is a unique $i_* \in I$ such that $\nu_2(i_*) = M$.*

Proof. For $\Delta = 0$, uniqueness holds because between any two integers i, i' with $\nu_2(i) = \nu_2(i')$, there exists i'' with $\nu_2(i'') > \nu_2(i)$. We prove the $\Delta > 0$ case by induction on M. The base case $M = 0$ is trivial. For the inductive step, let I_L be the set of elements of I less than i_*, and let I_R be the set of elements of I greater than i_*. By the uniqueness of i_*, every $i \in I_L \cup I_R$ satisfies $\nu_2(i) \leq M - 1$. Therefore, by induction, the number of $i \in I_L$ such that $\nu_2(i) = M - \Delta$ is at most $2^{\Delta-1}$, and the number of $i \in I_R$ such that $\nu_2(i) = M - \Delta$ is also at most $2^{\Delta-1}$. □

Now let G be a simple width-w length-n layered digraph, and let s and t be vertices, say in layers i and i' respectively, where $i' \geq i+2$. Let i_* be the unique layer in $\{i+1, i+2, \ldots, i'-1\}$ that maximizes $\nu_2(i_*)$. Let $U^{s\to t}$ be the set of vertices u in layer i_* such that u is reachable from s and t is reachable from u.

The analysis is based on the same basic principle as Van Melkebeek and Prakriya's analysis [vMP19], which is that a minimum-weight path from s to t consists of a minimum-weight path from s to u, followed by a minimum-weight path from u to t, for an optimal choice $u \in U^{s\to t}$. Motivated by this principle, for each $u \in U^{s\to t}$ and each seed x, let $D^{s\to u\to t}(x)$ be the minimum weight of a path that goes from s to t via u with respect to the weight function ρ_x. We would like to avoid the situation that $D^{s\to u\to t}(x) = D^{s\to v\to t}(x)$ for two distinct $u, v \in U^{s\to t}$. To argue that this bad event is unlikely, we use the discrete partial derivative operator.

Definition 2.2 (Discrete partial derivative)**.** Let $f\colon \{0,1\}^\ell \to \mathbb{R}$ and let $j \in [\ell]$. We define

$$\partial_j f(x) = f(x_{j\leftarrow 1}) - f(x_{j\leftarrow 0}),$$

where $x_{j\leftarrow b}$ is the string obtained from x by replacing its j-th bit with b.

Let $B_j = 6^{\nu_2(i_*)+\ell-j}$ for each $j \in [\ell]$. We will show that $\partial_j D^{s\to u\to t}(x) \approx B_j \cdot C(u)_j$. Specifically:

Lemma 2.3 (Derivatives of $D^{s\to u\to t}$)**.** *For every $j \in [\ell]$, $u \in U^{s\to t}$, and $x \in \{0,1\}^\ell$, we have*

$$\partial_j D^{s\to u\to t}(x) \in [B_j \cdot C(u)_j, B_j \cdot (C(u)_j + 1/2)].$$

Proof. First let P be a fixed path from s to t that visits u. When we flip x_j from 0 to 1, how much does $\rho_x(P)$ increase?

- The weight $\rho_x(u)$ increases by precisely $B_j \cdot C(u)_j$.
- By Lemma 2.1, the sum of the weights of the other internal vertices of P increases by at most $\sum_{\Delta=1}^{\infty} 2^\Delta \cdot 6^{-\Delta} \cdot B_j = B_j/2$.

Thus, if we let $f_P(x) = \rho_x(P)$, then $\partial_j f_P(x) \in [B_j \cdot C(u)_j, B_j \cdot (C(u)_j + 1/2)]$.

Now let P_0 and P_1 be minimum-weight paths from s to t visiting u with respect to the weight functions $\rho_{x_{j\leftarrow 0}}$ and $\rho_{x_{j\leftarrow 1}}$, respectively. The two paths P_0 and P_1 are not necessarily equal. Nevertheless, we can reason as follows. On the one hand, we have

$$\begin{aligned}
\rho_{x_{j\leftarrow 1}}(P_1) - \rho_{x_{j\leftarrow 0}}(P_0) &= \Big(\rho_{x_{j\leftarrow 1}}(P_1) - \rho_{x_{j\leftarrow 1}}(P_0)\Big) + \Big(\rho_{x_{j\leftarrow 1}}(P_0) - \rho_{x_{j\leftarrow 0}}(P_0)\Big) \\
&= \Big(\text{something non-positive}\Big) + \Big(\partial_j f_{P_0}(x)\Big) \\
&\leq B_j \cdot (C(u)_j + 1/2).
\end{aligned}$$

On the other hand, we have

$$\begin{aligned}
\rho_{x_{j\leftarrow 1}}(P_1) - \rho_{x_{j\leftarrow 0}}(P_0) &= \Big(\rho_{x_{j\leftarrow 1}}(P_1) - \rho_{x_{j\leftarrow 0}}(P_1)\Big) + \Big(\rho_{x_{j\leftarrow 0}}(P_1) - \rho_{x_{j\leftarrow 0}}(P_0)\Big) \\
&= \Big(\partial_j f_{P_1}(x)\Big) + \Big(\text{something non-negative}\Big) \\
&\geq B_j \cdot C(u)_j.
\end{aligned}$$

The lemma follows. □

Now we are ready to show that the weight function ρ_x is min-isolating for most seeds x. Recall that d is the minimum distance of the code C.

Theorem 2.4. *Sample a seed $x \in \{0,1\}^\ell$ uniformly at random. Then*

$$\Pr_x[\rho_x \text{ is not min-isolating for } G] \le 2^{-d} \cdot w^4 \cdot n^2.$$

Proof. Fix vertices s, t and distinct $u, v \in U^{s\to t}$. Let $E_{s,t,u,v}$ be the set of "bad" seeds, i.e., seeds x such that

$$D^{s\to u\to t}(x) = D^{s\to v\to t}(x).$$

Let $x \in E_{s,t,u,v}$, and let y be a distinct seed that agrees with x in every coordinate j such that $C(u)_j = C(v)_j$. Imagine transforming x into y by flipping one bit at a time, starting from the first coordinate j_* in which they differ and moving to the right. Initially, we have $D^{s\to u\to t}(x) = D^{s\to v\to t}(x)$. By Lemma 2.3, the first flip changes one of $D^{s\to u\to t}(x), D^{s\to v\to t}(x)$ by at least B_{j_*} in absolute value, namely the one with $C(\cdot)_{j_*} = 1$, while it changes the other by at most $B_{j_*}/2$. Furthermore, by Lemma 2.3, each subsequent flip, say in position j, changes each value by at most $(3/2) \cdot B_j$, and both changes have the same sign. Therefore,

$$\begin{aligned}|D^{s\to u\to t}(y) - D^{s\to v\to t}(y)| &\ge (1/2)\cdot B_{j_*} - \sum_{j=j_*+1}^{\ell} (3/2)\cdot B_j > B_{j_*}\cdot\left((1/2) - (3/2)\cdot\sum_{\Delta=1}^{\infty} 6^{-\Delta}\right)\\ &= B_{j_*}\cdot((1/2) - (3/2)\cdot(1/5))\\ &> 0.\end{aligned}$$

This shows that $y \notin E_{s,t,u,v}$. Thus, we have shown that every two distinct $x, y \in E_{s,t,u,v}$ must disagree in some coordinate where $C(u)$ and $C(v)$ agree, hence

$$|E_{s,t,u,v}| \le 2^{|\{j : C(u)_j = C(v)_j\}|} \le 2^{\ell-d}.$$

Now we do a union bound over all s, t, u, v. The number of choices for s and t is $\binom{n}{2}\cdot w^2$. After fixing s and t, the number of choices for u, v is at most $\binom{w}{2}$. So overall, the probability that any bad event $E_{s,t,u,v}$ occurs is at most $2^{-d}\cdot\binom{n}{2}\cdot\binom{w}{2}\cdot w^2 < 2^{-d}\cdot n^2\cdot w^4$.

Now assume that none of the bad events $E_{s,t,u,v}$ occurs. Under this assumption, we will show that ρ_x is min-isolating for G. Fix any s and t such that t is reachable from s. We prove that the minimum-weight path from s to t is unique by induction on the length k of paths from s to t. The base cases $k \in \{0,1\}$ are trivial. If $k \ge 2$, then the assumption implies that every minimum-weight path from s to t passes through the same $u \in U^{s\to t}$. By induction, the minimum-weight path from s to u is unique, and the minimum-weight path from u to t is unique. Consequently, the minimum-weight path from s to t is unique. □

Theorem 1.3 immediately follows by choosing a large enough $d = O(\log(wn))$.

AI Disclosure

I used GPT-6.2 Astra to discover the proof and help with preparing this paper. I acknowledge that I am responsible for all claims in the paper.

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