

Characterizing NC^1 with Typed Monoids

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Abstract

Krebs et al. (2007) gave a characterization of the complexity class TC^0 as the class of languages recognized by a certain class of typed monoids. The notion of typed monoid was introduced to extend methods of algebraic automata theory to infinite monoids and hence characterize classes beyond the regular languages. We advance this line of work beyond TC^0 by giving a characterization of NC^1 . This is obtained by first showing that NC^1 can be defined as the languages expressible in an extension of first-order logic using only unary quantifiers over regular languages. The expressibility result is a consequence of a general result showing that finite monoid multiplication quantifiers of higher dimension can be replaced with unary quantifiers in the context of interpretations over strings, which also answers a question of Lautemann et al. (2001).

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23 **1** Introduction

24 Much work in theoretical computer science is concerned with studying classes of formal
 25 languages, whether these are classes defined in terms of grammars and expressions, such as
 26 the class of regular or context-free languages, or whether they are *complexity classes* such as
 27 P and NP, defined by resource bounds on machine models. Indeed, the distinction between
 28 these are largely historical as most classes of interest admit different characterizations based
 29 on machine models, grammars, logical definability, or algebraic expressions. The class of
 30 regular languages can be characterized as the languages accepted by linear-time-bounded
 31 single-tape Turing machines [9] while P can be characterized without reference to resources
 32 as the languages recognized by multi-head two-way pushdown automata [6]. The advantage
 33 of the variety of characterizations is, of course, the fact that these bring with them different
 34 mathematical toolkits that can be brought to the study of the classes.

35 The class of regular languages has arguably the richest theory in this sense of diversity
 36 of characterizations. Virtually all students of computer science learn of the equivalence of
 37 deterministic and nondeterministic finite automata, regular languages and linear grammars
 38 and many also know that the regular languages are exactly those definable in monadic
 39 second-order logic with an order predicate. Perhaps the most productive approach to the
 40 study of regular languages is via their connection to finite monoids. Every language L has a
 41 syntactic monoid, which is finite if, and only if, L is regular. Moreover, closure properties of
 42 classes of regular languages relate to natural closure properties of classes of monoids, via
 43 Eilenberg’s Correspondence Theorem [8]. This, together with the tools of *Krohn-Rhodes*
 44 *theory*, gives rise to *algebraic automata theory*—which leads to the definition of natural
 45 subclasses of the class of regular languages, to effective decision procedures for automata
 46 recognizing such classes, and to separation results.

47 When it comes to studying computational complexity, we are mainly interested in classes
 48 of languages richer than just the regular languages. Thus the syntactic monoids of the
 49 languages are not necessarily finite any longer and the extensive tools of Krohn-Rhodes
 50 theory are not available to study them. Nonetheless, some attempts have been made to extend
 51 the methods of algebraic automata theory to classes beyond the regular languages. Most
 52 significant is the work of Krebs and collaborators [2, 3, 11, 10, 5], which introduces the notion
 53 of *typed monoids*. The idea is to allow for languages with infinite syntactic monoids, but limit
 54 the languages they recognize by associating with them a finite collection of types. This allows
 55 for the formulation of a version of Eilenberg’s Correspondence theorem associating closure
 56 properties on classes of typed monoids with corresponding closure properties of classes of
 57 languages. In particular, this implies that most complexity classes of interest can be uniquely
 58 characterized in terms of an associated class of typed monoids [3]. An explicit description
 59 of the class characterizing DLOGTIME-uniform TC^0 is given in [11, 10]. This is obtained
 60 through a general method which allows us to construct typed monoids corresponding to
 61 *unary quantifiers* defined from specific languages [10] (see also Theorem 22 below).

62 In this paper, we extend this work to obtain a characterization of DLOGTIME-uniform
 63 NC^1 as the class of languages recognized by the collection of typed monoids obtained as the
 64 closure under *ordered strong block products* of three typed monoids: the group of integers
 65 with types for positive and negative integers; the group of natural numbers with types for
 66 the square numbers and non-square numbers; and a finite non-solvable group such as S_5 with
 67 a type for each subset of the group. Full definitions of these terms follow below. Our result
 68 is obtained by first characterizing DLOGTIME-uniform NC^1 in terms of logical definability
 69 in an extension of first-order logic with only unary quantifiers. It is known that any regular

language whose syntactic monoid is a non-solvable group is complete for NC^1 under reductions definable in first-order logic with arithmetic predicates ($\text{FO}(+, \times)$) [1]. From this, we know we can describe NC^1 as the class of languages definable in an extension of $\text{FO}(+, \times)$ with quantifiers (of arbitrary arity) associated with the regular languages recognized by the monoid S_5 . Our main technical contribution is to show that the family of such quantifiers associated with any finite monoid can be replaced with just the unary quantifiers. This also answers a question left open in [13].

In Section 2, we cover the relevant background material on semigroup theory, typed monoids, and multiplication quantifiers. In Section 3, we establish the main technical result showing that quantifiers of higher arity over a regular language L can be defined using just unary quantifiers over the syntactic monoid of L . Finally, in Section 4, we apply this to obtain the algebraic characterization of $\text{DLOGTIME-uniform NC}^1$.

2 Preliminaries

We assume the reader is familiar with basic concepts of formal language theory, automata theory, complexity theory, and logic. We quickly review definitions we need to fix notation and establish conventions.

We write \mathbb{Z} for the set of integers, \mathbb{N} for the set of natural numbers (including 0), and \mathbb{Z}^+ for the set of positive integers. We write $[n]$ for the set of integers $\{1, \dots, n\}$ and \mathbb{S} for the set of *square* integers. That is, $\mathbb{S} = \{x \in \mathbb{Z}^+ \mid x = y^2 \text{ for some } y \in \mathbb{Z}\}$.

For a fixed $n \in \mathbb{Z}^+$ and an integer $i \in [n]$, we define the *n-bit one-hot encoding* of i to be the binary string $b \in \{0, 1\}^n$ such that $b_j = 1$ if, and only if, $j = i$.

2.1 Semigroups, Monoids and Groups

A *semigroup* (S, \cdot) is a set S equipped with an *associative* binary operation. We call a semigroup *finite* if S is finite. Context permitting, we may refer to a semigroup (S, \cdot) simply by its underlying set S . A *monoid* (M, \cdot) is a semigroup with a distinguished element $1_M \in M$ such that for all $m \in M$, $1_M \cdot m = m \cdot 1_M = m$. We call 1_M the *identity* or *neutral* element of M . A *group* (G, \cdot) is a monoid such that for every $g \in G$, there exists an element $g^{-1} \in G$ such that $g \cdot g^{-1} = g^{-1} \cdot g = 1$. We call g^{-1} the *inverse* of g .

Note that $(\mathbb{Z}, +)$ is a group, $(\mathbb{N}, +)$ is a monoid but not a group and $(\mathbb{Z}^+, +)$ is a semigroup but not a monoid. In the first two cases, the identity element is 0. When we refer to the monoids \mathbb{Z} or \mathbb{N} we assume that the operation referred to is standard addition.

For a semigroup (S, \cdot) , we say that a set $G \subseteq S$ *generates* S if S is equal to the closure of G under \cdot ; we denote this by $S = \langle G \rangle$, or, simply, $\langle G \rangle$ if the operation is clear from context, and call G a *generating set* of S . We say that S is *finitely generated* if there exists a finite generating set of S . All semigroups we consider are finitely generated. Note that \mathbb{Z}^+ is generated by $\{1\}$, \mathbb{N} by $\{0, 1\}$ and \mathbb{Z} by $\{1, -1\}$.

We write U_1 for the monoid $(\{0, 1\}, \cdot)$ where the binary operation is the standard multiplication. Note that 1 is the identity element here. For any set S , we denote by S^+ the set of non-empty finite strings over S and by S^* the set of all finite strings over S . Equipped with the concatenation operation on strings, which we denote by either \circ or simply juxtaposition, S^* is a monoid and S^+ is a semigroup but not a monoid. We refer to these as the *free monoid* and *free semigroup* over S , respectively. Note that S is a set of generators for S^+ and $S \cup \{\epsilon\}$ is a set of generators for S^* .

A monoid homomorphism from a monoid (S, \cdot_S) to a monoid (T, \cdot_T) is a function $h : S \rightarrow T$ such that for all $s_1, s_2 \in S$, $h(s_1 \cdot_S s_2) = h(s_1) \cdot_T h(s_2)$ and $h(1_S) = 1_T$. A *congruence* on

a monoid (M, \cdot) is an equivalence relation \sim on M such that for all $a, b, c, d \in M$, if $a \sim b$ and $c \sim d$, then $a \cdot c \sim b \cdot d$. We denote by M/\sim the set of equivalence classes of \sim on M . We denote by $[a]_\sim$, or simply $[a]$, the equivalence class of $a \in M$ under \sim . Any congruence \sim gives rise to the *quotient monoid* of M by \sim , namely the monoid $(M/\sim, \star)$ where for $[a], [b] \in M/\sim$, $[a] \star [b] = [a \cdot b]$. The map $\eta : M \rightarrow M/\sim$ defined by $\eta(a) = [a]$ is then a homomorphism, known as the *canonical homomorphism* of M onto M/\sim .

For future reference, we formally define the syntactic congruence associated with a language L .

► **Definition 1.** Let $L \subseteq \Sigma^*$ be a language. We define the syntactic congruence of L as the equivalence relation \sim_L on Σ^* such that for all $x, y \in \Sigma^*$, $x \sim_L y$ if and only if for all $w, v \in \Sigma^*$, $wxy \in L$ iff $wyv \in L$.

It is easily seen that this relation is a congruence on the free monoid Σ^* . The quotient monoid Σ^*/\sim_L is known as the *syntactic monoid* of L . More generally, we say that a monoid M recognizes the language L if there is a homomorphism $h : \Sigma^* \rightarrow M$ and a set $A \subseteq M$ such that $L = h^{-1}(A)$. It is easily seen that the syntactic monoid of L recognizes L . A language is regular if, and only if, its syntactic monoid is finite.

2.2 Logics and Quantifiers

We assume familiarity with the basic syntax and semantics of first-order logic. In this paper, the logic is always interpreted in finite relational structures. We generally denote structures by Fraktur letters, \mathfrak{A} , \mathfrak{B} , etc., and the corresponding universe of the structure is denoted $|\mathfrak{A}|$, $|\mathfrak{B}|$, etc. We are almost exclusively interested in *strings* over a finite alphabet. Thus, fix an alphabet Σ . A Σ -string is then a structure \mathfrak{A} whose universe A is linearly ordered by a binary relation $<$ and which interprets a set of unary relation symbols $(R_\sigma)_{\sigma \in \Sigma}$. For each element $a \in |\mathfrak{A}|$ there is a unique $\sigma \in \Sigma$ such that a is in the interpretation of R_σ .

More generally, let τ be any relational vocabulary consisting of a binary relation symbol $<$ and unary relation symbols R_1, \dots, R_k . We can associate with any τ -structure in which $<$ is a linear order a string over an alphabet of size 2^k as formalized in the following definition.

► **Definition 2.** For τ a relational vocabulary consisting of a binary relation symbol $<$ and unary relation symbols R_1, \dots, R_k , and \mathfrak{A} a τ -structure with n elements that interprets the symbol $<$ as a linear order of its universe, we define the string $w_{\mathfrak{A}}$ associated with \mathfrak{A} as the string of length n over the alphabet $\Sigma_k = \{0, 1\}^k$ of size 2^k so that if a is the i th element of $w_{\mathfrak{A}}$, then a is the k -tuple where $a_j = 1$ if, and only if, R_j holds at the i th element of \mathfrak{A} .

This way, we can associate a language with any isomorphism-closed class of structures over the vocabulary τ . We formalize this definition for future use.

► **Definition 3.** For τ a relational vocabulary consisting of a binary relation symbol $<$ and unary relation symbols R_1, \dots, R_k , and \mathcal{A} a class of τ -structures, we define the language $L_{\mathcal{A}}$ over the alphabet $\Sigma_k = \{0, 1\}^k$ to be

$$L_{\mathcal{A}} = \{w_{\mathfrak{A}} \mid \mathfrak{A} \in \mathcal{A}\}.$$

Conversely, for any language L over the alphabet Σ_k , we define the class of τ -structures \mathcal{S}_L to be

$$\mathcal{S}_L = \{\mathfrak{A} \mid w_{\mathfrak{A}} \in L\}.$$

As the elements of a string \mathfrak{A} are linearly ordered, we can identify them with an initial segment $\{1, \dots, n\}$ of the positive integers. In other words, we treat a string with universe $\{1, \dots, n\}$ and the standard order on these elements as a canonical representative of its isomorphism class. In addition to the order predicate, we may allow other *numerical predicates* to appear in formulas of our logics. These are predicates whose meaning is completely determined by the size n of the structure and the ordering of its elements. In particular, we have ternary predicates $+$ and \times for the partial addition and multiplication functions.

An insight due to Lindström allows us to define a *quantifier* from any isomorphism-closed class of structures (see [7]). Specifically, let Q be any isomorphism-closed class of structures in a relational vocabulary $\tau = \{R_1, \dots, R_l\}$, where for each i , R_i is a relation symbol of arity r_i . For any vocabulary σ and positive integer d , an *interpretation* of τ in σ of dimension d is a tuple of formulas $I = (\phi_1(\bar{x}_1), \dots, \phi_l(\bar{x}_l))$ of vocabulary σ where ϕ_i is associated with a tuple \bar{x}_i of variables of length dr_i . Suppose we are given a σ -structure \mathfrak{A} and an assignment α that takes variables to elements of \mathfrak{A} . Then let $\phi_i^{\mathfrak{A}, \alpha}$ denote the relation of arity dr_i consisting of the set of tuples $\{\bar{a} \in |\mathfrak{A}|^{dr_i} \mid \mathfrak{A} \models \phi_i[\alpha[\bar{a}/\bar{x}_i]]\}$. Then, the interpretation I defines a map that takes a σ -structure \mathfrak{A} , along with an assignment α to the τ -structure $I(\mathfrak{A}, \alpha)$ with universe $|\mathfrak{A}|^d$ where the interpretation of R_i is the set $\phi_i^{\mathfrak{A}, \alpha}$, seen as a relation of arity r_i on $|\mathfrak{A}|^d$.

Then, in a logic with quantifier Q , we can form formulas of the form

$$Q\bar{x}_1 \cdots \bar{x}_l(\phi_1, \dots, \phi_l)$$

in which occurrences in the subformula ϕ_i of variables among x_i are bound. The semantics of this quantifier are given by the rule that $Q\bar{x}_1 \cdots \bar{x}_l(\phi_1, \dots, \phi_l)$ is true in a structure \mathfrak{A} under some interpretation α of values to the free variables if the τ -structure $I(\mathfrak{A}, \alpha)$ is in Q . Note, we have defined what are usually called *vectorized quantifiers*, in that they can take interpretations of any dimension. Another way of formulating this is to have a separate quantifier Q_d for each dimension d . We switch between these notations when it causes no confusion and we call Q_d the *vectorization* of Q of dimension d .

We are particularly interested in interpretations I where both σ and τ are vocabularies of strings. These are also known in the literature as *string-to-string transducers* (see [4] for an example of how transducers may have many representations.) We further restrict ourselves to interpretations in which the definition of the linear order in $I(\mathfrak{A}, \alpha)$ is always the lexicographic order on d -tuples of \mathfrak{A} induced by the order in \mathfrak{A} . This order is easily defined by a (quantifier-free) first-order formula, and we simply omit it from the description of I . Hence, we only need to specify the interpretation giving the unary relations in τ and an interpretation of dimension d has the simple form $(\phi_1(\bar{x}_1), \dots, \phi_l(\bar{x}_l))$, where all tuples of variables have length d . We can then assume, without loss of generality, that they are all the same tuple \bar{x} and we thus write a formula with a string quantifier Q as

$$Q\bar{x}(\phi_1, \dots, \phi_l).$$

Observe that a quantifier applied to an interpretation of dimension d will then bind d variables.

We say that an interpretation is *unary* if it has dimension 1. We now introduce some notation we use in the rest of the paper for various logics formed by combining particular choices of quantifiers and numerical predicates.

► **Definition 4.** For a set of quantifiers \mathfrak{Q} and numerical predicates \mathfrak{N} , we denote by $(\mathfrak{Q})[\mathfrak{N}]$ the logic constructed by extending quantifier-free first-order logic with the quantifiers in \mathfrak{Q} and allowing the numerical predicates in \mathfrak{N} .

182 We denote by FO the set of standard first-order quantifiers: $\{\exists, \forall\}$.

183 For a singleton set of quantifiers $\mathfrak{Q} = \{Q\}$, we sometimes denote $(\mathfrak{Q})[\mathfrak{N}]$ as $(Q)[\mathfrak{N}]$. We
 184 use similar notation for the sets of numerical predicates. We use $\mathcal{L}((\mathfrak{Q})[\mathfrak{N}])$ to denote
 185 the languages expressible by the logic $(\mathfrak{Q})[\mathfrak{N}]$. We also use $(\mathfrak{Q}_1)[\mathfrak{N}]$ to denote the logic
 186 obtained as a restriction of $(\mathfrak{Q})[\mathfrak{N}]$ to formulas in which quantifiers in \mathfrak{Q} are only applied to
 187 interpretations of dimension 1.

188 All the logics we consider are *substitution closed* in the sense of [7]. This means in particular
 189 that if a quantifier Q is definable in a logic $(\mathfrak{Q})[\mathfrak{N}]$, then extending the logic with the quantifier
 190 Q does not add to its expressive power. This is because we can replace occurrences of the
 191 quantifier Q by its definition, with a suitable substitution of the interpretation for the relation
 192 symbols. Hence, if Q is definable in $(\mathfrak{Q})[\mathfrak{N}]$, then $\mathcal{L}((\mathfrak{Q})[\mathfrak{N}]) = \mathcal{L}((\mathfrak{Q} \cup \{Q\})[\mathfrak{N}])$.

193 A remark is due on our notation for numerical predicates. All structures we consider
 194 are ordered, including those defining the quantifiers. Thus the order predicate is implicitly
 195 present in the collection of numerical predicates \mathfrak{N} and is used (implicitly) to define the
 196 interpretations to a quantifier. We sometimes write $(\mathfrak{Q})[\emptyset]$ to indicate a logic in which this
 197 is the only use of the order that is allowed. By our choice of notation, the order symbol then
 198 does not appear explicitly in the syntax of the formulas.

199 2.3 Multiplication Quantifiers

200 The definition of multiplication quantifier has its origin in Barrington, Immerman, and
 201 Straubing [1, Section 5] where they were referred to as monoid quantifiers; the authors
 202 proved that the languages in DLOGTIME-uniform NC¹ are exactly those expressible by
 203 first-order logic with quantifiers whose truth-value is determined via multiplication in a finite
 204 monoid. The notion was extended by Lautemann et al. [13] to include quantifiers for the word
 205 problem over more general algebras with a binary operation. Multiplication quantifiers over
 206 a finite monoid M can be understood as generalized quantifiers corresponding to languages
 207 recognized by M , and here we define them as such.

Fix a monoid M , a set $B \subseteq M$ and a positive integer k . Let Σ_k denote the set $\{0, 1\}^k$
 which we think of as an alphabet of size 2^k , and fix a function $\gamma : \Sigma_k \rightarrow M$. We extend γ
 to strings in Σ_k^* inductively in the standard way: $\gamma(\epsilon) = 1_M$ and $\gamma(wa) = \gamma(w)\gamma(a)$. Together
 these define a language

$$L_{\gamma}^{M,B} = \{x \in \Sigma_k^* \mid \gamma(x) \in B\}.$$

208 We can now define a *multiplication quantifier*. In the following, \mathcal{S}_L denotes the class of
 209 structures associated with a language L in the sense of Definition 3.

210 ► **Definition 5.** Let τ be a vocabulary including an order symbol $<$ and k unary relations.
 211 For a monoid M , a set $B \subseteq M$, a positive integer k and a function $\gamma : \{0, 1\}^k \rightarrow M$,
 212 the multiplication quantifier $\Gamma_{\gamma}^{M,B}$ is the Lindström quantifier associated with the class of
 213 structures $\mathcal{S}_{L_{\gamma}^{M,B}}$.

214 We also write $\Gamma_{d,\gamma}^{M,B}$ for the vectorization of this quantifier of dimension d . If B is a
 215 singleton $\{s\}$, then we often write $\Gamma_{d,\gamma}^{M,s}$ for short.

216 Recall that U_1 denotes the two-element monoid $\{0, 1\}$ with standard multiplication. Then,
 217 it is easily seen that $\Gamma_{1,\gamma}^{U_1,0}$, where $\gamma : \{0, 1\} \rightarrow U_1$ such that $\gamma(0) = 1$ and $\gamma(1) = 0$, is the
 218 standard existential quantifier. The universal quantifier can be defined similarly.

219 ► **Definition 6.** For a monoid M , we define the following collections of quantifiers:

$$220 \quad \Gamma^M = \{\Gamma_{\gamma}^{M,B} \mid B \subseteq M, \gamma : \{0, 1\}^k \rightarrow M, \text{ and } k \geq 1\}$$

$$\Gamma_d^M = \left\{ \Gamma_{d,\gamma}^{M,B} \mid B \subseteq M \text{ and } \gamma : \{0,1\}^k \rightarrow M \right\}$$

$$\Gamma_\gamma^M = \left\{ \Gamma_\gamma^{M,B} \mid B \subseteq M \right\}$$

$$\Gamma_{d,\gamma}^M = \left\{ \Gamma_{d,\gamma}^{M,B} \mid B \subseteq M \right\}$$

Finally, let Γ^{fin} be the collection of all multiplication quantifiers over finite monoids.

From [1, Corollary 9.1], we know that DLOGTIME-uniform NC^1 is characterized by $(\text{FO})[+, \times]$ equipped with finite multiplication quantifiers:

► **Theorem 7** ([1]). $\text{DLOGTIME-uniform NC}^1 = \mathcal{L}((\Gamma^{\text{fin}})[+, \times])$.

► **Remark 8.** In fact, simply adding multiplication quantifiers for some fixed finite, non-solvable monoid to $(\text{FO})[+, \times]$ suffices. The definition of “non-solvable monoid” is not needed for our proofs here but, for example, the *symmetric group of degree five*, denoted S_5 , is a non-solvable monoid. Therefore, we know that $\text{DLOGTIME-uniform NC}^1 = \mathcal{L}((\text{FO} \cup \Gamma^{S_5})[+, \times])$.

In the absence of the arithmetic predicates for addition and multiplication, the logic of multiplication quantifiers over finite monoids only allows us to define regular languages. Specifically, Barrington et al. [1] established that the regular languages are characterized by the logic using such quantifiers with only unary interpretations.

► **Theorem 9** ([1]). $\text{REG} = \mathcal{L}((\Gamma_1^{\text{fin}})[<])$.

Later, Lautemann et al. [13, Theorem 5.1] showed that allowing interpretations of higher dimension to the quantifiers does not increase the expressive power when order is the only numerical predicate.

► **Theorem 10.** $\text{REG} = \mathcal{L}((\Gamma^{\text{fin}})[<])$.

Our main technical result shows that this is true even in the presence of other numerical predicates and, therefore, Γ^{fin} can be replaced by Γ_1^{fin} even in Theorem 7.

2.4 Typed Monoids

In this subsection, we review the definitions and results from [3, 10] on typed monoids, their relationship to languages and corresponding characterizations of complexity classes.

A typed monoid is a monoid equipped with a collection of *types*, which form a Boolean algebra, and a set of *units*. We only deal with concrete Boolean algebras, given as collections of subsets of a fixed universe.

► **Definition 11** (Boolean Algebra). A Boolean algebra over a set S is a set $B \subseteq \wp(S)$ such that $\emptyset, S \in B$ and B is closed under union, intersection, and complementation. If B is finite, we call it a finite Boolean algebra.

We call \emptyset and S the trivial elements (or in some contexts, the trivial types) of B .

A homomorphism between Boolean algebras is defined as standard. That is, if B_1 and B_2 are Boolean algebras over sets S and T , respectively, then we call $h : B_1 \rightarrow B_2$ a homomorphism if $h(\emptyset) = \emptyset$, $h(S) = T$, and for all $s_1, s_2 \in B_1$, $h(s_1 \cap s_2) = h(s_1) \cap h(s_2)$, $h(s_1 \cup s_2) = h(s_1) \cup h(s_2)$, and $h(s^C) = (h(s))^C$. Now we are ready to define typed monoids.

► **Definition 12** (Typed Monoid). Let M be a monoid, G a Boolean algebra over M , and E a finite subset of M . We call the tuple $T = (M, G, E)$ a typed monoid over M and the

elements of G types and the elements of E units. We call M the base monoid of T . If M is a group, then we may also call T a typed group.

Say $G = \{\emptyset, A, M - A, M\}$. Then, we often abbreviate T as (M, A, E) , i.e., the Boolean algebra is signified by an element, or elements, which generates it—in this case, A .

We say that a typed monoid (M, G, E) is finite if M is.

We also need a notion of morphism between typed monoids.

► **Definition 13.** A typed monoid homomorphism h from (S, G, E) to (T, H, F) is a triple (h_1, h_2, h_3) where $h_1 : S \rightarrow T$ is a monoid homomorphism, $h_2 : G \rightarrow H$ is a homomorphism of Boolean algebras, and $h_3 : E \rightarrow F$ is a mapping of sets such that the following conditions hold:

- (i) For all $A \in G$, $h_1(A) = h_2(A) \cap h_1(S)$.
- (ii) For all $e \in E$, $h_1(e) = h_3(e)$.

Note that h_3 is redundant in the definition as it is completely determined by h_1 . We retain it as part of the definition for consistency with [3, 10].

To motivate the definitions, recall that a language $L \subseteq \Sigma^*$ is recognized by a monoid M if there is a homomorphism $h : \Sigma^* \rightarrow M$ and a set $B \subseteq M$ such that $L = h^{-1}(B)$. When the monoid M is infinite, the languages recognized form a rather rich collection and we aim to restrict this in two ways. First, B cannot be an arbitrary set but must be an element of the algebra of types. Secondly, the homomorphism h must map the letters in Σ to units of the typed monoid. Formally, we have the following definition.

► **Definition 14.** A typed monoid $T = (M, G, E)$ recognizes a language $L \subseteq \Sigma^*$ if there exists a typed monoid homomorphism from (Σ^*, L, Σ) to T . We let $\mathcal{L}(T)$ denote the set of languages recognized by T .

When the base monoid of a typed monoid is finite, we recover the classical definition of a recognition. Hence, the languages recognized by finite typed monoids are necessarily regular.

► **Proposition 15.** If T is a finite typed monoid, then $\mathcal{L}(T) \subseteq \text{REG}$.

We can now state the definitions of the key relationships between typed monoids.

► **Definition 16.** Let (S, G, E) and (T, H, F) be typed monoids.

- A typed monoid homomorphism $h = (h_1, h_2, h_3) : (S, G, E) \rightarrow (T, H, F)$ is injective (surjective, or bijective) if all of h_1 , h_2 , and h_3 are.
- (S, G, E) is a typed submonoid (or, simply, “submonoid” when context is obvious) of (T, H, F) , denoted $(S, G, E) \leq (T, H, F)$, if there exists an injective typed monoid homomorphism $h : (S, G, E) \rightarrow (T, H, F)$.
- (S, G, E) divides (T, H, F) , denoted $(S, G, E) \preceq (T, H, F)$, if there exists a surjective typed monoid homomorphism from a typed submonoid of (T, H, F) to (S, G, E) .

These have the expected properties.

► **Proposition 17 ([3]).** Let T_1 , T_2 , and T_3 be typed monoids.

- Typed monoid homomorphisms are closed under composition.
- Division is transitive: if $T_1 \preceq T_2$ and $T_2 \preceq T_3$, then $T_1 \preceq T_3$.
- If $T_1 \preceq T_2$, then $\mathcal{L}(T_1) \subseteq \mathcal{L}(T_2)$.

We can formulate the notion of the syntactic typed monoid of a language L as an extension of the syntactic monoid of L with a minimal collection of types and units necessary.

301 ► **Definition 18.** Let $T = (M, G, E)$ be a typed monoid. A congruence \sim over M is a typed
 302 congruence over T if for every $A \in G$ and $s_1, s_2 \in M$, if $s_1 \sim s_2$ and $s_1 \in A$, then $s_2 \in A$.
 303 For a typed congruence \sim over T , let

$$\begin{aligned} 304 \quad A/\sim &= \{[x]_\sim \mid x \in A\} \text{ where } A \subseteq M \\ 305 \quad G/\sim &= \{A/\sim \mid A \in G\} \\ 306 \quad E/\sim &= \{[x]_\sim \mid x \in E\}. \end{aligned}$$

307 Then, $T/\sim := (M/\sim, G/\sim, E/\sim)$ is the typed quotient monoid of T by \sim .

308 Let \sim_T denote the typed congruence on T such that for $s_1, s_2 \in S$, $s_1 \sim_T s_2$ iff for all
 309 $x, y \in S$ and $A \in G$, $xs_1y \in A$ iff $xs_2y \in A$. We then refer to the quotient monoid T/\sim_T as
 310 the minimal reduced monoid of T .

311 Recall that \sim_L is the syntactic congruence of L , defined in Definition 1.

312 ► **Definition 19.** For a language $L \subseteq \Sigma^*$, the syntactic typed monoid of L , denoted $\text{syn}(L)$,
 313 is the typed monoid $(\Sigma^*, L, \Sigma)/\sim_L$.

314 We also get the canonical typed monoid homomorphism, $\eta_L : (\Sigma^*, L, \Sigma) \rightarrow \text{syn}(L)$ induced
 315 by the syntactic homomorphism of L .

316 We now turn to the relationship between the expressive power of logics with multiplication
 317 quantifiers and typed monoids. A formal association is defined through the definition below.

318 ► **Definition 20.** For a multiplication quantifier $Q = \Gamma_\gamma^{M,B}$ where $\gamma : \{0, 1\}^k \rightarrow M$, we define
 319 the typed quantifier monoid of Q to be the syntactic typed monoid of the language $L_\gamma^{M,B}$.

320 It turns out that we can give a purely structural characterization of those typed monoids
 321 that are syntactic monoids.

322 ► **Proposition 21** ([10]). A typed monoid is the syntactic monoid of a language if, and only
 323 if, it is reduced, generated by its units, and has four or two types.

324 In case it has just two types, then it only recognizes the empty language or the language
 325 of all strings.

326 We now want to state the formal connection between the languages expressible in a logic
 327 with a collection of quantifiers and the corresponding class of typed monoids. For this we
 328 need the notion of the *ordered strong block product closure* of a set of typed monoids T ,
 329 which we denote $\text{sbpc}_<(T)$. The definition is technical and can be found in [10] and is also
 330 reproduced in the appendix for ease of reference.

331 From [10, Theorem 4.14], we then get the following relationship between logics and
 332 algebras:¹

333 ► **Theorem 22.** Let \mathfrak{Q} be a collection of quantifiers and \mathbf{Q} the corresponding set of typed
 334 quantifier monoids for \mathfrak{Q} . Then, $\mathcal{L}((\mathfrak{Q}_1)[<]) = \mathcal{L}(\text{sbpc}_<(\mathbf{Q}))$.

335 Recall that “ \mathfrak{Q}_1 ” here is used to denote the restriction of our logic to only uses where
 336 quantifiers are applied to interpretations of dimension 1.

¹ The theorem in [10] is actually more general as it allows for more predicates than just order; however, for our purposes, order alone suffices.

3 Simplifying Multiplication Quantifiers

To use Theorem 22 to obtain an algebraic characterization of NC^1 , we need to characterize this class in a logic with only unary quantifiers, i.e. where quantifiers are only applied to unary interpretations. Remark 8 gives us a characterization using first-order quantifiers and Γ^{S_5} . Our aim in this section is to show that we can eliminate the use of interpretations of dimension higher than 1 in this logic. As a first step, we show that we can restrict ourselves to quantifiers $\Gamma_\delta^{S_5, B}$ for a fixed function δ .

► **Lemma 23.** *For every finite monoid M , there exists a function $\delta : \{0, 1\}^{|M|} \rightarrow M$ such that for every $B \subseteq M$ and $\gamma : \{0, 1\}^k \rightarrow M$, the quantifier $\Gamma_\gamma^{M, B}$ is definable in $(\Gamma_\delta^{M, B})[\emptyset]$.*

Proof. Recall that $\Gamma_\gamma^{M, B}$ is the class of structures \mathfrak{A} in a vocabulary τ with one binary relation $<$ and k unary relations R_1, \dots, R_k such that $\gamma(w_\mathfrak{A}) \in B$ where $w_\mathfrak{A}$ is the string associated with \mathfrak{A} as in Def. 2.

Let $c = |M|$, fix an enumeration $\{s_1, \dots, s_c\}$ of M , and let z be an arbitrary element of M . Let $\delta : \{0, 1\}^c \rightarrow M$ be the function where $\delta(w) = s_i$ if w is the one-hot encoding of i and $\delta(w) = z$ otherwise (that is, if the number of occurrences of the symbol 1 in the string w is not exactly one).

For each $t \in M$, define the formula $\psi_t(x)$ as follows:

$$\psi_t(x) := \bigvee_{w \in \{0, 1\}^k : \gamma(w) = t} \left(\bigwedge_{i \in [k] : w_i = 1} R_i(x) \wedge \bigwedge_{i \in [k] : w_i = 0} \neg R_i(x) \right).$$

It is easy to see that in a τ -structure \mathfrak{A} , we have $\mathfrak{A} \models \psi_t[a]$ if, and only if, the a th element of $w_\mathfrak{A}$ is mapped by γ to t . Thus, in particular, the formulas $\psi_{s_1}, \dots, \psi_{s_c}$ define disjoint sets that partition the universe of \mathfrak{A} . We now claim that the quantifier $\Gamma_\gamma^{M, B}$ is defined by the formula:

$$\Gamma_\delta^{M, B}(\psi_{s_1} \dots, \psi_{s_c}).$$

To see this, let I denote the unary interpretation $(\psi_{s_1} \dots, \psi_{s_c})$ so that $w_{I(\mathfrak{A})}$ is a string over $\{0, 1\}^c$. By the fact that the sets defined by the formulas $\psi_{s_1}, \dots, \psi_{s_c}$ partition $|\mathfrak{A}|$ it follows that each letter of $w_{I(\mathfrak{A})}$ is a vector in $\{0, 1\}^c$ with exactly one 1. Indeed, the a th element of $w_{I(\mathfrak{A})}$ is the one-hot encoding of i precisely if $\mathfrak{A} \models \psi_{s_i}[a]$. Since δ takes the one-hot encoding of i to s_i , we have for any $a \in |\mathfrak{A}|$

$$\delta((w_{I(\mathfrak{A})})_a) = s_i$$

$$\text{iff } \mathfrak{A} \models \psi_i[a]$$

$$\text{iff } \gamma((w_\mathfrak{A})_a) = s_i.$$

Hence, $\delta(w_{I(\mathfrak{A})}) = \gamma(w_\mathfrak{A})$ and therefore $I(\mathfrak{A}) \in \Gamma_\delta^{S, B}$ if, and only if, $\mathfrak{A} \in \Gamma_\gamma^{M, B}$ as required. ◀

It then follows from Lemma 23 and the substitution property of quantifiers that the expressive power of $(\mathfrak{Q} \cup \Gamma^M)[\mathfrak{N}]$ is the same as that of $(\mathfrak{Q} \cup \Gamma_\delta^M)[\mathfrak{N}]$. Indeed, any application of a quantifier in Γ^M to an interpretation of dimension d can be replaced by an application of a quantifier in Γ_δ^M to an interpretation of the same dimension. We next aim to show that an application of a quantifier $\Gamma_\delta^{M, B}$ to an interpretation of dimension d can be replaced by d nested applications of quantifiers to interpretations of dimension 1.

► **Lemma 24.** *For any collection \mathfrak{Q} of quantifiers, any formula of $(\mathfrak{Q} \cup \Gamma_\delta^M)[\mathfrak{N}]$ is equivalent to one of $(\mathfrak{Q} \cup \Gamma_{1, \delta}^M)[\mathfrak{N}]$.*

Proof. Again, fix an enumeration $M = \{s_1, \dots, s_c\}$ of M and recall that $\delta : \{0, 1\}^c \rightarrow M$ takes the one-hot encoding of i to s_i .

We show, by induction on d that if we have a formula

$$\Phi := \Gamma_{\delta}^{M,B} x_1, \dots, x_d (\phi_1(x_1, \dots, x_d), \dots, \phi_c(x_1, \dots, x_d))$$

where each formula ϕ_i is in $(\mathfrak{Q} \cup \Gamma_{1,\delta}^M)[\mathfrak{N}]$, then Φ is equivalent to a formula of $(\mathfrak{Q} \cup \Gamma_{1,\delta}^M)[\mathfrak{N}]$. The result then follows by induction on the structure of the formula.

The base case when $d = 1$ is trivially true. Assume then that we have the formula Φ for $d > 1$ and let I denote the interpretation $(\phi_1(x_1, \dots, x_d), \dots, \phi_c(x_1, \dots, x_d))$ of dimension d .

We claim that Φ is equivalent to the formula

$$\Phi_1 := \Gamma_{\delta}^{M,B} x_1 (\theta_1(x_1), \dots, \theta_c(x_1))$$

where θ_i is the formula

$$\theta_i(x_i) := \Gamma_{\delta}^{M,s_i} x_2, \dots, x_d (\phi_1(x_1, \dots, x_d), \dots, \phi_c(x_1, \dots, x_d)).$$

Thus, Φ_1 is obtained by the application of $\Gamma_{\delta}^{M,B}$ to a unary interpretation

$$I_1 := (\theta_1(x_1), \dots, \theta_c(x_1))$$

where each formula θ_i is obtained as the application of a quantifier Γ_{δ}^{M,s_i} to an interpretation of dimension $d - 1$ defined by formulas of $(\mathfrak{Q} \cup \Gamma_{1,\delta}^M)[\mathfrak{N}]$. Thus, by the inductive hypothesis, each θ_i is equivalent to a formula of $(\mathfrak{Q} \cup \Gamma_{1,\delta}^M)[\mathfrak{N}]$ and we are done.

It remains to show that Φ and Φ_1 are equivalent on any string structure \mathfrak{A} . To see this, fix an assignment α of values in $|\mathfrak{A}|$ to the free variables of Φ . We need to show that $\mathfrak{A} \models \Phi[\alpha]$ if, and only if, $\mathfrak{A} \models \Phi_1[\alpha]$. Let n be the length of \mathfrak{A} and assume without loss of generality that the elements of $|\mathfrak{A}|$ are $\{1, \dots, n\}$ in that order.

Now, $w_{I(\mathfrak{A},\alpha)}$ denotes the string associated with the structure $I(\mathfrak{A},\alpha)$ and note that this is a string of length n^d whose elements are indexed by d -tuples of elements of \mathfrak{A} . By definition, $\mathfrak{A} \models \Phi[\alpha]$ precisely if $\delta(w_{I(\mathfrak{A},\alpha)}) \in B$. We can also regard I as an interpretation of dimension $d - 1$ obtained by treating the variable x_1 as a parameter. We write $w_{I(\mathfrak{A},\alpha[a/x_1])}$ for the string of length n^{d-1} that results from applying this interpretation with the assignment of a to the variable x_1 . Since the ordering of d -tuples in $w_{I(\mathfrak{A},\alpha)}$ is lexicographic, we have

$$w_{I(\mathfrak{A},\alpha)} = w_{I(\mathfrak{A},\alpha[1/x_1])} \cdots w_{I(\mathfrak{A},\alpha[n/x_1])}$$

and thus

$$\delta(w_{I(\mathfrak{A},\alpha)}) = \delta(w_{I(\mathfrak{A},\alpha[1/x_1])}) \cdots \delta(w_{I(\mathfrak{A},\alpha[n/x_1])}).$$

Now, by definition of θ_i , we have $\mathfrak{A} \models \theta_i[\alpha[a/x_1]]$ if, and only if, $\delta(w_{I(\mathfrak{A},\alpha[a/x_1])}) = s_i$. Thus, for each $a \in |\mathfrak{A}|$, there is exactly one i such that $\mathfrak{A} \models \theta_i[\alpha[a/x_1]]$. Thus, $w_{I_1(\mathfrak{A},\alpha)}$ is the string of length n whose a th element is the one-hot encoding of i exactly when $\delta(w_{I(\mathfrak{A},\alpha[a/x_1])}) = s_i$. In other words, $\delta((w_{I_1(\mathfrak{A},\alpha)})_a) = \delta(w_{I(\mathfrak{A},\alpha[a/x_1])})$. Thus,

$$\mathfrak{A} \models \Phi[\alpha]$$

$$\text{iff } \delta(w_{I(\mathfrak{A},\alpha)}) \in B$$

$$\text{iff } \delta(w_{I(\mathfrak{A},\alpha[1/x_1])}) \cdots \delta(w_{I(\mathfrak{A},\alpha[n/x_1])}) \in B$$

$$\text{iff } \delta((w_{I_1(\mathfrak{A},\alpha)})_1) \cdots \delta((w_{I_1(\mathfrak{A},\alpha)})_n) \in B$$

$$\text{iff } \delta(w_{I_1(\mathfrak{A},\alpha)}) \in B$$

$$\text{iff } \mathfrak{A} \models \Phi_1[\alpha].$$



23:12 Characterizing NC^1 with Typed Monoids

Now we are ready to state the main theorem of this section.

► **Theorem 25.** *For every finite monoid M , there exists a function $\delta : \{0, 1\}^{|M|} \rightarrow M$ such that for any collection of quantifiers \mathfrak{Q} and any set \mathfrak{N} of numerical predicates, every formula of $(\mathfrak{Q} \cup \Gamma^M)[\mathfrak{N}]$ is equivalent to a formula of $(\mathfrak{Q} \cup \Gamma_{1,\delta}^M)[\mathfrak{N}]$.*

Proof. Let ϕ be any formula of $(\mathfrak{Q} \cup \Gamma^M)[\mathfrak{N}]$. By Lemma 23 we can replace all occurrences of quantifiers $\Gamma_{\gamma}^{M,B}$ by their definitions using $\Gamma_{\delta}^{M,B}$ to get a formula ϕ' of $(\mathfrak{Q} \cup \Gamma_{\delta}^M)[\mathfrak{N}]$ equivalent to ϕ . Finally, by Lemma 24, there is a formula of $(\mathfrak{Q} \cup \Gamma_{1,\delta}^M)[\mathfrak{N}]$ equivalent to ϕ' . ◀

Note that for a finite monoid M , while Γ^M and Γ_1^M are infinite sets, $\Gamma_{1,\delta}^M$ is a finite set. Therefore, this gives us a logic characterizing $\text{DLOGTIME-uniform NC}^1$ which not only uses unary quantifiers but also only has a finite number of quantifiers:

► **Corollary 26.** *There exists a $\delta : \{0, 1\}^k \rightarrow S_5$ such that*

$$\text{DLOGTIME-uniform NC}^1 = \mathcal{L}((\text{FO} \cup \Gamma_{1,\delta}^{S_5})[+, \times])$$

This simplifies our construction of an algebra capturing $\text{DLOGTIME-uniform NC}^1$.

Moreover, this theorem serves as an alternative proof of Theorem 10 ([13, Theorem 5.1]) which, unlike the original proof, does not rely on the use of automata. Furthermore, resolves an open question from [13]:

► **Corollary 27.** $\mathcal{L}((\Gamma^{\text{fin}})[+, \times]) = \mathcal{L}((\Gamma_1^{\text{fin}})[+, \times])$

4 The Algebraic Characterization

Now that we have an extension of first-order logic capturing $\text{DLOGTIME-uniform NC}^1$ using only quantifiers acting on unary interpretations of unary dimension, we are able to apply Theorem 22 to construct an algebra for it. We just need to obtain an equivalent logic using only the numerical predicate $<$ without introducing quantifiers of higher dimension.

To do this, we follow the construction of an algebra for TC^0 . The *majority* quantifier Maj is the collection of strings over the alphabet $\{0, 1\}$ in which at least half of the symbols are 1. The *square* quantifier Sq is the collection of strings over the alphabet $\{0, 1\}$ in which the number of 1s is a positive square number (i.e. and element of \mathbb{S}). In the logics we define below, we always use these quantifiers only with unary interpretations.

The following lemma displays some known results about the expressiveness of these quantifiers:

► **Lemma 28.**

- (i) Maj is definable in $(\Gamma^{\text{fin}})[+, \times]$. (cf. [1])
- (ii) The quantifiers in FO are definable in $(\text{Maj})[<]$. ([12, Theorem 3.2])
- (iii) The numerical predicate $+$ is definable in $(\text{Maj})[<]$. ([12, Theorem 4.1])
- (iv) The numerical predicate \times is definable in $(\{\text{Maj}, \text{Sq}\})[<]$ and Sq is definable in $(\text{Maj})[<, +, \times]$. (cf. [15, Theorem 2.3.f] and [11, Section 2.3])

Bringing everything together, we get the following algebraic characterization of $\text{DLOGTIME-uniform NC}^1$:

► **Theorem 29.**

$$\text{DLOGTIME-uniform NC}^1 = \mathcal{L}(\text{sbpc}_{<}(\{(\mathbb{Z}, \mathbb{Z}^+, \pm 1), (\mathbb{N}, \mathbb{S}, \{0, 1\}), (S_5, \wp(S_5), S_5)\})).$$

Proof. Let $\delta : \{0, 1\}^c \rightarrow S_5$ be as it was defined in Lemma 23. It is easy to see that the typed quantifier monoid for Maj is $(\mathbb{Z}, \mathbb{Z}^+, \pm 1)$, for Sq is $(\mathbb{N}, \mathbb{S}, \{0, 1\})$, and for $\Gamma_{1,\delta}^{S_5, s}$ is $(S_5, \{s\}, S_5)$.

By Corollary 26, we have that

$$\text{DLOGTIME-uniform NC}^1 = \mathcal{L}((\text{FO} \cup \Gamma_{1,\delta}^{S_5})[+, \times]).$$

Lemma 28 (ii)–(iv) allow us to define FO, +, and \times in $(\{\text{Maj}, \text{Sq}\})[<]$ and (i) and (iv) allow us to define Maj and Sq in $(\text{FO} \cup \Gamma_{1,\delta}^{S_5})[+, \times]$. Therefore,

$$\text{DLOGTIME-uniform NC}^1 = \mathcal{L}((\Gamma_{1,\delta}^{S_5} \cup \{\text{Maj}, \text{Sq}\})[<]).$$

Theorem 22 gives us the algebraic characterization of

$$\begin{aligned} \text{DLOGTIME-uniform NC}^1 = \mathcal{L}(\text{sbpc}_{<}(\{(\mathbb{Z}, \mathbb{Z}^+, \pm 1), (\mathbb{N}, \mathbb{S}, \{0, 1\})\} \\ \cup \{(S_5, A, S_5) \mid A \in \wp(S_5)\})) \end{aligned}$$

Because $(S_5, A, S_5) \prec (S_5, \wp(S_5), S_5)$ for all $A \in \wp(S_5)$, we lose no expressive power by consolidating all elements (S_5, A, S_5) with $(S_5, \wp(S_5), S_5)$. We neither gain expressive power because $\mathcal{L}((S_5, \wp(S_5), S_5)) \subseteq \text{REG} \subseteq \text{DLOGTIME-uniform NC}^1$. Therefore, we have our final characterization:

$$\text{DLOGTIME-uniform NC}^1 = \mathcal{L}(\text{sbpc}_{<}(\{(\mathbb{Z}, \mathbb{Z}^+, \pm 1), (\mathbb{N}, \mathbb{S}, \{0, 1\}), (S_5, \wp(S_5), S_5)\})).$$

5 Conclusion

In this work, we constructed a class of typed monoids exactly recognizing DLOGTIME-uniform NC¹. To do so, we proved results regarding the expressive power of logics with quantifiers defined over finite monoids. Specifically, we established that the expressive power is not changed by restricting the dimension of the interpretations on which the quantifiers act, regardless of which numerical predicates are available.

Therefore, we were able to provide a logic characterizing DLOGTIME-uniform NC¹ which only uses unary quantifiers and use this logic to construct an algebraic characterization of DLOGTIME-uniform NC¹. This result marks the second circuit complexity class to be characterized in a such a way, with the first being DLOGTIME-uniform TC⁰ [11].

An interesting future direction would be to construct similar algebraic characterization of other complexity classes beyond NC¹. It seems this would require the development of new algebraic tools. In particular, the block product is a key tool used to characterize first-order quantification and more generally quantification over interpretations of dimension one. To extend the work to other complexity classes, it would be worthwhile investigating other product constructions that might similarly relate to quantification on interpretations of higher dimension as well as higher-order quantifiers.

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517 **A Strong Block Product Closure**

518 **A.1 Weakly Closed Classes**

519 ► **Definition 30** (Direct Product of Monoids). *The direct product of two monoids (S, \cdot_S) and*
520 *(T, \cdot_T) is the monoid $(S \times T, \cdot)$ where $(s_1, t_1) \cdot (s_2, t_2) = (s_1 \cdot_S s_2, t_1 \cdot_T t_2)$.*

521 ► **Definition 31** (Direct Product of Boolean Algebras). *We define the direct product of*
522 *Boolean algebras B_1 and B_2 , denoted $B_1 \times B_2$, to be the Boolean algebra generated by the set*
523 *$\{A_1 \times A_2 \mid A_1 \in B_1 \text{ and } A_2 \in B_2\}$.*

524 ► **Definition 32** (Direct Product of Typed Monoids).
525 *The direct product $(S, G, E) \times (T, H, F)$ is the typed monoid $(S \times T, G \times H, E \times F)$.*

526 ► **Definition 33** (Trivial Extension). *If there exists a surjective typed monoid homomorphism*
527 *from (S, G, E) to (T, H, F) , then we say that (S, G, E) is a trivial extension of (T, H, F) .*

528 ► **Definition 34** (Weakly Closed Class). *We call a set of typed monoids T a weakly closed*
529 *class if it is closed under*

- 530 ■ *Division: If $(S, G, E) \in T$ and $(S, G, E) \preceq (T, H, F)$, then $(T, H, F) \in T$.*
- 531 ■ *Direct Product: If $(S, G, E), (T, H, F) \in T$, then $(S, G, E) \times (T, H, F) \in T$.*
- 532 ■ *Trivial Extension: If (S, G, E) is a trivial extension of (T, H, F) and $(T, H, F) \in T$, then*
533 *$(S, G, E) \in T$.*

534 *We write $\text{wc}(T)$ to denote the smallest weakly closed set of typed monoids containing T .*

A.2 The Block Product

The block product will be our main tool for the construction of algebraic characterizations of language classes via logic. Historically, the “*wreath product*” was first used for this purpose. Since [14], however, the block product has typically been the preferred and easier-to-work-with tool of choice. We now build up to its definition:

► **Definition 35** (Left and Right Actions). *A left action \star_l of a monoid (N, \cdot) on a monoid $(M, +)$ is a function from $N \times M$ to M such that for $n, n_1, n_2 \in N$ and $m, m_1, m_2 \in M$,*

$$n \star_l (m_1 + m_2) = n \star_l m_1 + n \star_l m_2$$

$$(n_1 \cdot n_2) \star_l m = n_1 \star_l (n_2 \star_l m)$$

$$n \star_l 1_M = 1_M$$

$$1_N \star_l m = m$$

The right action \star_r of (N, \cdot) on $(M, +)$ is defined dually. We say that left and right actions of (N, \cdot) on $(M, +)$ are compatible if for all $n_1, n_2 \in N$ and $m \in M$,

$$(n_1 \star_l m) \star_r n_2 = n_1 \star_l (m \star_r n_2).$$

When clear from context, we may simply write nm for $n \star_l m$ and mn for $m \star_r n$.

► **Definition 36** (Two-sided Semidirect Product). *For a pair of compatible left and right actions, \star_l and \star_r of (N, \cdot) on $(M, +)$, the two-sided (or bilateral) semidirect product of $(M, +)$ and (N, \cdot) with respect to \star_l and \star_r is the monoid $(M \times N, \star)$ where for $(m_1, n_1), (m_2, n_2) \in M \times N$,*

$$(m_1, n_1) \star (m_2, n_2) = (m_1 n_2 + n_1 m_2, n_1 \cdot n_2).$$

► **Definition 37** (Block Product). *The block product of (M, \cdot_M) with (N, \cdot_N) , denoted $M \square N$, is the two-sided semidirect product of $(M^{N \times N}, +)$ and (N, \cdot) with respect to the left and right actions \star_l and \star_r where for $f, g \in M^{N \times N}$ and $n, n_1, n_2 \in N^1$,*

■ $(M^{N \times N}, +)$ is the monoid of all functions from $N \times N$ to M under componentwise product $+$:

$$(f + g)(n_1, n_2) = f(n_1, n_2) \cdot_M g(n_1, n_2).$$

■ The left action \star_l of (N, \cdot) on $(M^{N \times N}, +)$ is defined by

$$(n \star_l f)(n_1, n_2) = f(n_1 \cdot_N n, n_2).$$

■ The right action \star_r of (N, \cdot) on $(M^{N \times N}, +)$ is defined by

$$(f \star_r n)(n_1, n_2) = f(n_1, n \cdot_N n_2).$$

A.3 The Typed Block Product

► **Definition 38** (Typed Block Product). *Let (S, G, E) and (S', G', E') be typed monoids and $C \subseteq S'$ be a finite set. Then, the typed block product with C of (S, G, E) and (S', G', E') , denoted $(S, G, E) \square_C (S', G', E')$, is the typed monoid (T, H, F) where*

(1) $T \leq S \square S'$ such that T is generated by the elements (f, s') such that

(a) $s' \in E' \cup C$ and

(b) $f \in E^{S' \times S'}$ such that for $b_1, b_2, b_3, b_4 \in S'$, if for all $c \in C$ and all $A' \in G'$, $b_1 c b_2 \in A'$ iff $b_3 c b_4 \in A'$, then $f(b_1, b_2) = f(b_3, b_4)$,

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- 572 (2) $H = \{(f, s) \mid f(1, 1) \in A\} \mid A \in G\}$ where 1 is the identity of S' ,
 573 (3) and $F = \{(f, s') \mid (f, s) \text{ is a generator of } T \text{ and } s' \in E'\}.$

574 ► **Definition 39.** Because the typed monoid corresponding to the order predicate will be a very
 575 common, it is convenient to define an ordered typed block product, $(S, G, E) \boxtimes_C (S', G', E')$
 576 which will help simplify our algebraic representations whose numerical predicates only include
 577 order; this is defined the same as the typed block product above but with a change to condition
 578 (1)(b):

- 579 (1)(b_<) $f \in E^{S' \times S'}$ such that for $b_1, b_2, b_3, b_4 \in S'$, if for all $c \in C$ and all $A' \in G'$,
 580 (i) $b_1 c b_2 \in A'$ iff $b_3 c b_4 \in A'$,
 581 (ii) $b_1 c \in A'$ iff $b_3 c \in A'$,
 582 (iii) and $c b_2 \in A'$ iff $c b_4 \in A'$,
 583 then $f(b_1, b_2) = f(b_3, b_4).$

584 ► **Definition 40.** For a set of typed monoids W , we let

585 $W_0 = \text{wc}(W)$

586 and for each $k \geq 1$,

587 ■ $W_k = \{S_1 \boxtimes_C S_2 \mid S_1 \in W_0, S_2 \in W_{k-1}, \text{ and finite } C \subseteq S_2\}$

588 ■ $W_k^< = \{S_1 \boxtimes_C S_2 \mid S_1 \in W_0, S_2 \in W_{k-1}^<, \text{ and finite } C \subseteq S_2\}$

589 We define the (ordered) strong block product closure of W , denoted $\text{sbpc}(W)$ ($\text{sbpc}_<(W)$), as

590 ■ $\text{sbpc}(W) = \bigcup_{k \in \mathbb{N}} W_k$

591 ■ $\text{sbpc}_<(W) = \bigcup_{k \in \mathbb{N}} W_k^<.$