

Quotient Complexity of Star-Free Languages *

Janusz Brzozowski and Bo Liu

David R. Cheriton School of Computer Science, University of Waterloo,
Waterloo, ON, Canada N2L 3G1
{brzozo,b23liu}@uwaterloo.ca

Abstract

The quotient complexity, also known as state complexity, of a regular language is the number of distinct left quotients of the language. The quotient complexity of an operation is the maximal quotient complexity of the language resulting from the operation, as a function of the quotient complexities of the operands. The class of star-free languages is the smallest class containing the finite languages and closed under boolean operations and concatenation. We prove that the tight bounds on the quotient complexities of union, intersection, difference, symmetric difference, concatenation, and star for star-free languages are the same as those for regular languages, with some small exceptions, whereas the bound for reversal is $2^n - 1$.

Keywords: aperiodic, automaton, language, operation, quotient, regular, star-free, state complexity

1 Introduction

The class of regular languages can be defined as the smallest class containing the finite languages and closed under union, concatenation and star. Since regular languages are also closed under complementation, one can redefine them as the smallest class containing the finite languages and closed under boolean operations, concatenation and star. In this new formulation, a natural question is that of the *generalized star height* of a regular language, which is the minimum number of nested stars required to define the language when boolean operations are allowed. It is not clear who first considered the problem of generalized star height, but McNaughton and Papert reported in their 1971 monograph [17] that this problem

*This work was supported by the Natural Sciences and Engineering Research Council of Canada under grant No. OGP0000871.

had been open “for many years”. There exist regular languages of star height 0 and 1, but it is not even known whether there exists a language of star height 2. See <http://liafa.jussieu.fr/~jep/Problemes/starheight.html>.

We consider regular languages of star height 0, which are also called *star-free*. In 1965, Schützenberger proved [19] that a language is star-free if and only if its syntactic monoid is *group-free*, that is, has only trivial subgroups. An equivalent condition is that the minimal deterministic automaton of a star-free language is *permutation-free*, that is, has no permutations of any subset of states other than the identity permutation. Such automata are called *aperiodic*, and this is the term that we use.

The *state complexity* of a regular language [20] is the number of states in the complete minimal deterministic finite automaton accepting that language. We prefer the equivalent concept of *quotient complexity* [3], which is the number of distinct left quotients of the language, because quotient complexity has some advantages [3]. The *quotient complexity of an operation* in a subclass of regular languages is the maximal quotient complexity of the language resulting from the operation, as a function of the quotient complexities of the operands, when they range over all the languages in the subclass. The quotient complexities of operations on regular languages were studied by Maslov [16] and Yu *et al.* [21].

The quotient complexities of operations were also considered in several subclasses of regular languages: unary [18, 21], finite [9, 20], cofinite [1], ideal [5], closed [7], prefix-free [13], suffix-free [12], bifix-, factor-, and subword-free [6], and convex [4]. The quotient complexities can be significantly lower in a subclass of regular languages. We prove that this is *not* the case for star-free languages, which meet the bounds for regular languages, with a few small exceptions. Interestingly, the recent work in [14] shows that star-free languages also meet the bounds on the nondeterministic state complexity of operations for regular languages in most cases. As well, the tight bound for converting an n -state aperiodic nondeterministic automaton to a deterministic one is 2^n [2] (Theorem 9).

In Section 2 we define our terminology. Boolean operations, concatenation, star, and reversal are studied in Sections 3–6. Unary languages are treated in Section 7, and Section 8 concludes the paper. For omitted proofs see [8].

2 Terminology and Notation

If Σ is a finite non-empty alphabet, then Σ^* is the set of all words over this alphabet, with ε as the empty word. For $w \in \Sigma^*$, $a \in \Sigma$, let $|w|$ be the length of w , and $|w|_a$, the number of a 's in w . A language is any subset of Σ^* .

We use the following set operations on languages: *complement* ($\bar{L} = \Sigma^* \setminus L$),

union ($K \cup L$), intersection ($K \cap L$), difference ($K \setminus L$), and symmetric difference ($K \oplus L$). We also use *product*, also called (*con*)*catenation* ($KL = \{w \in \Sigma^* \mid w = uv, u \in K, v \in L\}$) and *star* ($K^* = \bigcup_{i \geq 0} K^i$). The *reverse* w^R of a word $w \in \Sigma^*$ is defined by: $\varepsilon^R = \varepsilon$, and $(wa)^R = aw^R$. The *reverse* of a language L is $L^R = \{w^R \mid w \in L\}$.

Regular languages are the smallest class of languages containing the finite languages and closed under boolean operations, product and star. *Star-free* languages are the languages one can construct from finite languages using only boolean operations and concatenation. Some examples of star-free languages are \emptyset , $\Sigma^* = \overline{\emptyset}$, $\{b\}^* = \overline{\Sigma^* \{a\} \Sigma^*} = \overline{\emptyset \{a\} \emptyset}$ over $\Sigma = \{a, b\}$, and $\{a\} \{a\}^* = \overline{\{\varepsilon\}}$ over $\Sigma = \{a\}$. We denote star-free languages by the usual regular expressions.

The (*left*) *quotient* of a language L by a word w is defined as $L_w = \{x \in \Sigma^* \mid wx \in L\}$. The number of distinct quotients of a language is called its *quotient complexity* and is denoted by $\kappa(L)$. A quotient L_w is *accepting* if $\varepsilon \in L_w$; otherwise it is *rejecting*.

A *deterministic finite automaton (DFA)* is a quintuple $\mathcal{D} = (Q, \Sigma, \delta, q_0, F)$, where Q is a finite non-empty set of *states*, Σ is a finite non-empty *alphabet*, $\delta : Q \times \Sigma \rightarrow Q$ is the *transition function*, q_0 is the *initial state*, and $F \subseteq Q$ is the set of *final* or *accepting states*. As usual, the transition function is extended to $Q \times \Sigma^*$. A DFA \mathcal{D} accepts $w \in \Sigma^*$ if $\delta(q_0, w) \in F$, and the *language* accepted by \mathcal{D} is $L(\mathcal{D})$. The *language of a state* q of \mathcal{D} is the language L_q accepted by the automaton $(Q, \Sigma, \delta, q, F)$. If the language of a state is empty, that state is *empty*.

Let $L^\varepsilon = \{\varepsilon\}$ if $\varepsilon \in L$, and $L^\varepsilon = \emptyset$, otherwise. The *quotient automaton* of a regular language L is $\mathcal{D} = (Q, \Sigma, \delta, q_0, F)$, where $Q = \{L_w \mid w \in \Sigma^*\}$, $\delta(L_w, a) = L_{wa}$, $q_0 = L_\varepsilon = L$, $F = \{L_w \mid L_w^\varepsilon = \{\varepsilon\}\}$, and $L_w^\varepsilon = (L_w)^\varepsilon$. Since this is the minimal DFA accepting L , the quotient complexity of L is equal to the state complexity of L .

A *transformation* of a set $S = \{1, \dots, n\}$ into itself is a mapping

$$t = \begin{pmatrix} 1 & 2 & \cdots & n-1 & n \\ i_1 & i_2 & \cdots & i_{n-1} & i_n \end{pmatrix},$$

where $i_k \in S$ for $1 \leq k \leq n$. Each word in Σ^* performs a transformation of the set Q of states of a DFA \mathcal{D} . A DFA is *aperiodic* if no word performs a permutation, other than the identity permutation, of a subset of Q . Since testing if a DFA is aperiodic is PSPACE-complete [10], we use a subclass of aperiodic automata. Without loss of generality, we assume that $Q = \{1, \dots, n\}$. A transformation is *non-decreasing* if $j < k$ implies $i_j \leq i_k$. A non-decreasing transformation cannot have a non-trivial permutation, and the composition of non-decreasing transformations is non-decreasing. Hence a DFA with non-decreasing input trans-

formations is aperiodic. All our examples use DFA's with non-decreasing input transformations, and so are aperiodic.

A *nondeterministic finite automaton (NFA)* is defined as a quintuple $\mathcal{N} = (Q, \Sigma, \eta, I, F)$, where Q , Σ , and F are as in a DFA, $\eta : Q \times \Sigma \rightarrow 2^Q$ is the *transition function* and $I \subseteq Q$ is the *set of initial states*. If η also allows ε , that is, $\eta : Q \times (\Sigma \cup \{\varepsilon\}) \rightarrow 2^Q$, we call \mathcal{N} an ε -NFA.

3 Boolean Operations

We now consider the quotient complexity of union, intersection, symmetric difference, and difference in the class of star-free languages. The upper bound for these four operations in the class of regular languages is mn [3, 16, 21].

Theorem 1. *For each of the operations union, intersection, symmetric difference, and difference, there exist binary star-free languages K and L with quotient complexities $m \geq 1$ and $n \geq 1$, respectively, that meet the bound mn .*

Proof. Let $\Sigma = \{a, b\}$. We examine union first. For $m = 1$, let $K = \emptyset$ and let L be any binary star-free language with $\kappa(L) = n$. Then $\kappa(K \cup L) = \kappa(L) = n = mn$. Similarly, if $n = 1$, let $L = \emptyset$ and let K be any binary star-free language with $\kappa(K) = m$. Then $\kappa(K \cup L) = mn$.

For $m, n \geq 2$, let $K = (b^*a)^{m-2}b^* = \{w \in \Sigma^* \mid |w|_a = m - 2\}$, and $L = (a^*b)^{n-2}a^* = \{w \in \Sigma^* \mid |w|_b = n - 2\}$; then $\kappa(K) = m$ and $\kappa(L) = n$. The quotient automata of K and L are in Fig. 1 for $m = 4$ and $n = 5$. Since the inputs of these automata perform non-decreasing transformations, the automata are aperiodic. The direct product for $K \cup L$ is shown in Fig. 2.

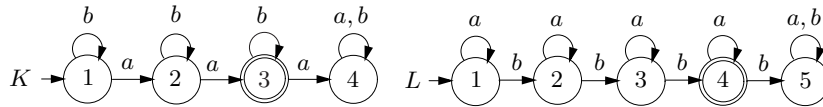


Figure 1: Witnesses K and L for union with $m = 4$ and $n = 5$.

Let $M = K \cup L$, and consider the mn words $a^i b^j$, $i = 0, \dots, m - 1$, and $j = 0, \dots, n - 1$; the quotients $M_{a^i b^j}$ correspond to states $(i + 1, j + 1)$ in the direct-product automaton for M . We begin with the rejecting quotients of M . First, $M_{a^{m-1} b^{n-1}} = \emptyset$, and all the other quotients are non-empty. If $i < m - 2$ and $j < n - 2$ (rows 1 to $m - 2$, columns 1 to $n - 2$), then the pair (a^{m-2-i}, b^{n-2-j}) of non-empty words belongs to $M_{a^i b^j}$ and to no other rejecting quotient. If $i < m - 2$, then $M_{a^i b^{n-1}}$ (rows 1 to $m - 2$, column n) contains a^{m-2-i} , but has no

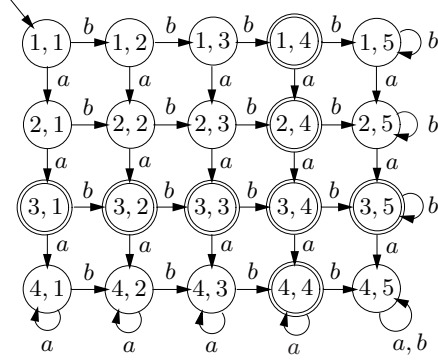


Figure 2: Quotient automaton of $K \cup L$.

words from b^* . If $j < n - 2$, then $M_{a^{m-1}b^j}$ (row m , columns 1 to $n - 2$) contains b^{n-2-j} , but has no words from a^* . So all rejecting quotients are distinct.

Now turn to the accepting quotients. For $i, k \leq m - 2$, quotient $M_{a^i b^{n-2}}$ (rows 1 to $m - 1$, column $n - 1$) contains ba^{m-2-i} , and this word is not contained in any other quotient $M_{a^k b^{n-2}}$ with $k \neq i$, and $M_{a^{m-1} b^{n-2}}$ has no words from ba^* . Thus all the quotients in column $n - 1$ are distinct. For $j, \ell \leq n - 2$, $M_{a^{m-2} b^j}$ (row $m - 1$, columns 1 to $n - 1$) contains ab^{n-2-j} , and this word is not contained in any other quotient $M_{a^{m-2} b^\ell}$ with $\ell \neq j$, and $M_{a^{m-2} b^{n-1}}$ has no words from ab^* . Thus all the quotients in row $m - 1$ are distinct. Excluding $M_{a^{m-2} b^{n-2}}$, each quotient in column $n - 1$ contains a but not b , each quotient in row $m - 1$ contains b but not a , and $M_{a^{m-2} b^{n-2}}$ contains both a and b . Hence all accepting quotients are distinct, and our claim holds for union.

For difference, we can use \overline{K} and L , where K and L meet the bound mn for union, because $\kappa(\overline{K} \setminus L) = \kappa(\overline{K} \cap \overline{L}) = \kappa(\overline{K} \cap \overline{L}) = \kappa(K \cup L)$. For intersection, we can use \overline{K} and \overline{L} , where K and L meet the bound mn for union, because $\kappa(\overline{K} \cap \overline{L}) = \kappa(\overline{K} \cap \overline{L}) = \kappa(K \cup L)$. The (star-free) languages $K = (b^*a)^{m-1}\Sigma^* = \{w \in \Sigma^* \mid |w|_a \geq m - 1\}$ and $L = (a^*b)^{n-1}\Sigma^* = \{w \in \Sigma^* \mid |w|_b \geq n - 1\}$ meet the bound mn for symmetric difference [5]. \square

4 Product

The tight bound for product of regular languages [16, 21] is $(m - 1)2^n + 2^{n-1}$. We show that this bound can be met by star-free languages, with some exceptions.

In subset constructions, we use the notation $S \xrightarrow{w} T$ to mean that subset S under input word w moves to subset T .

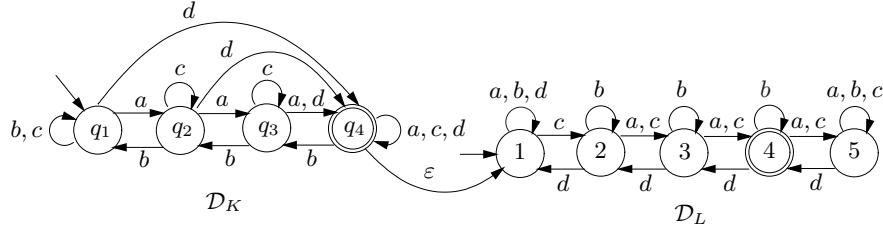


Figure 3: ε -NFA \mathcal{N} of KL .

Theorem 2. *There exist quaternary star-free languages K and L with $\kappa(K) = m \geq 1$ and $\kappa(L) = n \geq 3$, such that $\kappa(KL) = (m-1)2^n + 2^{n-1}$.*

Proof. Let the quotient automaton for K be $\mathcal{D}_K = (Q_K, \Sigma, \delta_K, q_0, F_K)$, where $Q_K = \{q_1, q_2, \dots, q_m\}$, $\Sigma = \{a, b, c, d\}$, $q_0 = q_1$, $F_K = \{q_m\}$, and

$$\begin{aligned} \delta_K(q_i, a) &= q_{i+1} \text{ for } i = 1, \dots, m-1, & \delta_K(q_m, a) &= q_m, \\ \delta_K(q_i, b) &= q_{i-1} \text{ for } i = 2, \dots, m, & \delta_K(q_1, b) &= q_1, \\ \delta_K(q_i, c) &= q_i \text{ for } i = 1, \dots, m, \\ \delta_K(q_i, d) &= q_m \text{ for } i = 1, \dots, m. \end{aligned}$$

Next, let the quotient automaton for L be $\mathcal{D}_L = (Q_L, \Sigma, \delta_L, p_0, F_L)$, where $Q_L = \{1, 2, \dots, n\}$, $\Sigma = \{a, b, c, d\}$, $p_0 = 1$, $F_L = \{n-1\}$, and

$$\begin{aligned} \delta_L(i, c) &= i+1 \text{ for } i = 1, \dots, n-1, & \delta_L(n, c) &= n, \\ \delta_L(i, d) &= i-1 \text{ for } i = 2, \dots, n, & \delta_L(1, d) &= 1, \\ \delta_L(i, a) &= i+1 \text{ for } i = 2, \dots, n-1, & \delta_L(1, a) &= 1, & \delta_L(n, a) &= n, \\ \delta_L(i, b) &= i \text{ for } i = 1, \dots, n. \end{aligned}$$

The automaton \mathcal{D}_K for $m = 4$ is shown in Fig. 3, where the transition labeled ε should be ignored for now. The automaton \mathcal{D}_L for $n = 5$ is also shown in Fig. 3. Since the inputs of these automata perform non-decreasing transformations, the automata are aperiodic. If the transition labeled ε is taken into account and q_4 is made a rejecting state, then we have an ε -NFA for KL . Here the initial state is q_1 , the set of accepting states is $\{4\}$, and the transitions are as shown.

Let $S = \{s_1, \dots, s_k\}$ be a set of states in Q_L , where $1 \leq s_1 < s_2 < \dots < s_k \leq n-1$. For $0 \leq x \leq n-s_k$, denote (s_1+x, \dots, s_k+x) by S_{+x} . Similarly, for $2 \leq s_1 \leq n$, and $0 \leq x \leq s_1-1$, denote (s_1-x, \dots, s_k-x) by S_{-x} .

We first show by induction on the size of S that all $(m-1)2^{n-1}$ subsets of the form $\{q_i\} \cup S$, where $q_i \in Q_K$, $q_i \neq q_m$, and $S \subseteq Q_L \setminus \{1\}$, are reachable.

When $S = \emptyset$, the set $\{q_i\}$ is reached by a^{i-1} , for $i = 1, \dots, m-1$. Now suppose we want to reach $\{q_i\} \cup T$, where $i \neq m$, $T = \{s_0, s_1, \dots, s_k\}$, $k \geq 0$, and $1 < s_0 < s_1 < \dots < s_k$. Let $S = \{s_1, \dots, s_k\}$; by the induction assumption, $\{q_i\} \cup S$ is reachable. Then $\{q_i\} \cup S \xrightarrow{d^{s_0-1}} \{q_m, 1\} \cup S_{-(s_0-1)} \xrightarrow{b^{m-i}} \{q_i, 1\} \cup S_{-(s_0-1)} \xrightarrow{c^{s_0-1}} \{q_i\} \cup \{s_0\} \cup S = \{q_i\} \cup T$. Thus $\{q_i\} \cup T$ is also reachable.

Next, we prove that the 2^{n-1} subsets of the form $\{q_m, 1\} \cup S$, where S is any subset of $Q_L \setminus \{1\}$, are reachable. If $m = 1$, then $\{q_1, 1\}$ is the initial subset. Let S and T be as above. Then $\{q_1, 1\} \cup S \xrightarrow{d^{s_0-1}} \{q_1, 1\} \cup S_{-(s_0-1)} \xrightarrow{c} \{q_1, 1\} \cup \{2\} \cup S_{-(s_0-2)} \xrightarrow{a^{s_0-2}} \{q_1, 1\} \cup \{s_0\} \cup S = \{q_1, 1\} \cup T$.

If $m \geq 2$, there are two cases. If $2 \notin S$, then start with $\{q_1\} \cup S$, which has already been shown to be reachable. We then have $\{q_1\} \cup S \xrightarrow{d} \{q_m, 1\} \cup S_{-1} \xrightarrow{a} \{q_m, 1\} \cup S$. If $2 \in S$, then start with $\{q_1\} \cup S \setminus \{2\}$. Now $\{q_1\} \cup S \setminus \{2\} \xrightarrow{d} \{q_m, 1\} \cup (S \setminus \{2\})_{-1} \xrightarrow{c} \{q_m, 1\} \cup \{2\} \cup (S \setminus \{2\}) = \{q_m, 1\} \cup S$.

Finally, we show that the $(m-1)2^{n-1}$ subsets of the form $\{q_i, 1\} \cup S$, where $i < m$, and $S \subseteq Q_L \setminus \{1\}$ are reachable. We have $\{q_m, 1\} \cup S \xrightarrow{b^{m-i}} \{q_i, 1\} \cup S$.

In summary, $(m-1)2^n + 2^{n-1}$ different subsets are reachable. We now prove that all these subsets are pairwise distinguishable.

For $1 \leq k \leq n-1$, state k of Q_L accepts the word $w_k = c^{n-1-k}$, and state n accepts the word $w_n = d$; moreover, each of these words w_h is accepted by only that one state h of Q_L , and none of these words is accepted by state q_i , if $i \neq m$. Hence, if h is in $S \setminus T$ or in $T \setminus S$, then S and T are distinguished by w_h .

First, let $1 \leq i \leq j < m$, and consider $\{q_i\} \cup S$ and $\{q_j\} \cup T$, where $S, T \subseteq Q_L$, and S and T differ by state h . Then $\{q_i\} \cup S$ and $\{q_j\} \cup T$ are distinguished by w_h . Next, let $1 \leq i < j < m$ and take $\{q_i\} \cup S$ and $\{q_j\} \cup S$, where $S \subseteq Q_L$. First apply c ; then we reach $\{q_i\} \cup R$ and $\{q_j\} \cup R$, where $1 \notin R$. Then $\{q_j\} \cup R$ accepts $a^{m-j}c^{n-2}$, whereas $\{q_i\} \cup R$ rejects this word.

Second, suppose $S, T \subseteq Q_L \setminus \{1\}$ and S and T differ by state h ; then $\{q_m, 1\} \cup S$ and $\{q_m, 1\} \cup T$ are distinguished by w_h .

Third, consider $\{q_i\} \cup S$, where $S \subseteq Q_L$ and $\{q_m, 1\} \cup T$, where $T \subseteq Q_L \setminus \{1\}$ and $i < m$. Then c^{n-1} is accepted by $\{q_m, 1\} \cup T$ but not by $\{q_i\} \cup S$.

Since all reachable sets are pairwise distinguishable, the bound is met. \square

Corollary 1. *There exists a ternary star-free language L with quotient complexity $n \geq 1$, such that $\kappa(\Sigma^*L) = 2^{n-1}$.*

Proof. If $K = \Sigma^*$, the DFA \mathcal{D}_K has one state, which is both initial and accepting. Now b is not needed in the proofs of reachability and distinguishability. \square

A *right (left) ideal* [5] is a language L satisfying $L = L\Sigma^*$ ($L = \Sigma^*L$). If $M = K\Sigma^*$ ($M = \Sigma^*K$), then M is the right (left) ideal generated by K . Corollary 1 shows that the bound 2^{n-1} on the quotient complexity of the left ideal generated by a regular language can also be met by a star-free language.

If $n = 1$ in Theorem 2, then either $KL = \emptyset$ and $\kappa(KL) = 1$, or $KL = K\Sigma^*$ is the right ideal generated by K . In the second case, it is known [21] that m is a tight bound for $\kappa(K\Sigma^*)$, and that the language $a^{m-1}a^*$ is a witness [5]. Since that witness is star-free, the general bound holds also for star-free languages.

The case $m \geq 2$ and $n = 2$ remains. For $m = n = 2$, the best bound for product of regular languages is 6, whereas it is 4 for star-free languages. This was verified with the *GAP* package *Automata* [11] by enumerating all products of 2-state aperiodic automata.

There are only three types of inputs possible for a 2-state aperiodic DFA: the input that takes both states to state 1, the input that takes both states to state 2, and the identity input. If 1 is the accepting state, then subsets $\{1\}$ and $\{1, 2\}$ are not distinguishable. Therefore a rejecting state q_i of \mathcal{D}_K can appear with only three subsets of states of \mathcal{D}_L in the DFA of KL : \emptyset , $\{1\}$, and $\{2\}$. An accepting state q_i of \mathcal{D}_K always appears with 1; hence we only have $\{q_i, 1\}$. The quotient complexity is maximized when there is only one accepting quotient of K . Hence $\kappa(KL) \leq (m-1)3 + 1 = 3m - 2$.

If 2 is the accepting state, then $\{2\}$ and $\{1, 2\}$ are not distinguishable. A rejecting state q_i of \mathcal{D}_K can appear only with three distinguishable subsets of S as above. An accepting state always appears with state 1 of \mathcal{D}_L ; hence we may have $\{q_m, 1\}$ and $\{q_m, 1, 2\}$. Therefore $\kappa(KL) \leq (m-1)3 + 2 = 3m - 1$ here.

Theorem 3. *There exist ternary star-free languages K and L with $\kappa(K) = m \geq 2$ and $\kappa(L) = 2$, such that $\kappa(KL) = 3m - 2$.*

Proof. Let $\mathcal{D}_K(a, b, c)$ be the DFA in the proof of Theorem 2 restricted to input alphabet $\{a, b, c\}$. Let $\mathcal{D}_L = (\{1, 2\}, \{a, b, c\}, \delta, 1, \{1\})$, where $\delta_L(i, a) = i$ for $i = 1, 2$, $\delta_L(i, b) = 1$ for $i = 1, 2$, and $\delta_L(i, c) = 2$ for $i = 1, 2$. It is shown in [8] that K and L meet the bound $3m - 2$. \square

We do not know whether the bound $3m - 1$ can be reached. However, we have verified with *GAP* that it cannot be reached if $m = 2$.

5 Star

The following DFA plays a key part in finding bounds on the quotient complexities of stars of star-free languages. Let $n \geq 3$, and $\mathcal{D}_n = \mathcal{D}_n(a, b, c, d) =$

$(Q, \{a, b, c, d\}, \delta, 1, \{n - 1\})$, where $Q = \{1, 2, \dots, n\}$ and

$$\begin{aligned} \delta(i, a) &= i + 1 \text{ for } i = 1, \dots, n - 1, & \delta(n, a) &= n, \\ \delta(i, b) &= i - 1 \text{ for } i = 2, \dots, n, & \delta(1, b) &= 1, \\ \delta(i, c) &= i - 1 \text{ for } i = 2, \dots, n - 1, & \delta(1, c) &= 1, & \delta(n, c) &= n, \\ \delta(i, d) &= n \text{ for } i = 1, \dots, n. \end{aligned}$$

Since all the inputs perform non-decreasing transformations, \mathcal{D}_n is aperiodic.

In Fig. 4, if we ignore state 0 and its outgoing transitions, and also the ε transition, then the figure shows the automaton $\mathcal{D}_7(a, b, c, d)$. With state 0 and the ε transition it depicts the ε -NFA of L^* .

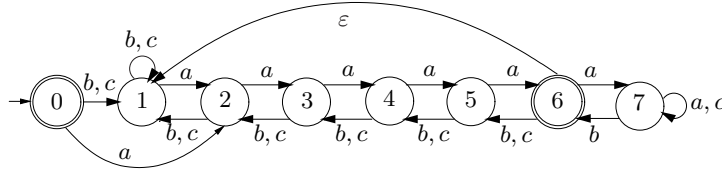


Figure 4: ε -NFA \mathcal{N} of L^* , $\kappa(L) = 7$. Transitions under d (not shown) are all to state 7.

We first study $\mathcal{D}_n(a, b)$, the restriction of $\mathcal{D}_n(a, b, c, d)$ to the alphabet $\{a, b\}$.

Lemma 1. *If $n \geq 3$, and L is the star-free language accepted by $\mathcal{D}_n(a, b)$, then $\kappa(L^*) = 2^{n-1} + 2^{n-3} - 1$.*

Proof. Consider the subsets of $\{0\} \cup Q$ in the subset construction of the DFA for L^* . Since 0 can only appear in $\{0\}$, the remaining reachable subsets are subsets of Q . The empty subset cannot be reached because there is a transition from each state under every letter. Since state $n - 1$ cannot occur without state 1, we eliminate 2^{n-2} subsets. Because state $n - 1$ always appears with state 1, and state n can only be reached from state $n - 1$ by a , the subset $\{n\}$ first appears with state 2, and afterwards, always with a state from $\{1, \dots, n - 1\}$; hence $\{n\}$ cannot be reached. Also, 1 and n cannot appear together without $n - 1$, because n cannot be reached by b , and 1 cannot be reached by a without including $n - 1$. This eliminates another 2^{n-3} subsets. So $1 + 2^{n-2} + 1 + 2^{n-3}$ subsets are unreachable, and $\kappa(L^*) \leq 2^n + 1 - (2^{n-2} + 2^{n-3} + 2) = 2^{n-1} + 2^{n-3} - 1$.

Now turn to the reachable subsets, and note that subsets $\{0\}$ and $\{1\}$ are reached by ε and b , respectively.

First, let $\mathbb{P} = \{S \subseteq \{2, \dots, n - 2\} \mid S \neq \emptyset\}$. All singleton sets $\{i\} \in \mathbb{P}$ are reached by a^{i-1} from $\{1\}$. Now let $S = \{s_1, \dots, s_k\}$, $T = \{s_0, s_1, \dots, s_k\}$,

where $0 < k$, $1 < s_0 < s_1 < \dots < s_k < n - 1$, and $h = n - 1 - s_k$; then $S \xrightarrow{a^h} \{1\} \cup S_{+h} \xrightarrow{b^h} \{1\} \cup S \xrightarrow{b^{s_0-1}} \{1\} \cup S_{-(s_0-1)} \xrightarrow{a^{s_0-1}} \{s_0\} \cup S$. Thus any $T \in \mathbb{P}$ can be reached from a smaller $S \in \mathbb{P}$, and so all subsets in \mathbb{P} are reachable.

Second, let $\mathbb{Q} = \{\{1\} \cup S \mid S \in \mathbb{P}\}$; then $S \xrightarrow{a^h b^h} \{1\} \cup S$, as above, and all subsets in \mathbb{Q} are reachable.

Third, let $\mathbb{R} = \{\{1, n - 1\} \cup S \mid S = \emptyset \text{ or } S \in \mathbb{P}\}$. If $S = \emptyset$, then $\{1, n - 1\}$ is reachable from $\{1\}$ by a^{n-2} . Now suppose $S \in \mathbb{P}$ is not empty. If $i \in S$, then $\{i\} \xrightarrow{a^{n-1-i}} \{1, n - 1\} \xrightarrow{a^{i-1}} \{i, n\}$. So $S \xrightarrow{a^{n-2}} \{n\} \cup S$. Now, if $s_k = n - 2$, then $\{n\} \cup S \xrightarrow{a} \{1, n - 1, n\} \cup S_{+1} \xrightarrow{b} \{1, n - 1\} \cup S$. If $s_k < n - 2$, then $\{n\} \cup S \xrightarrow{a} \{n\} \cup S_{+1} \xrightarrow{b} \{1, n - 1\} \cup S$. In either case, $S \xrightarrow{a^{n-1}b} \{1, n - 1\} \cup S$, and all 2^{n-3} subsets in \mathbb{R} are reachable.

Fourth, let $\mathbb{S} = \{\{n\} \cup T \mid T \in \mathbb{P} \cup \mathbb{R}\}$. We have shown that $S \xrightarrow{a^{n-2}} \{n\} \cup S$, if $S \in \mathbb{P}$. Since also $\{1, n - 1\} \xrightarrow{a^{n-2}} \{1, n - 1, n\}$, we have $\{1, n - 1\} \cup S \xrightarrow{a^{n-2}} \{1, n - 1, n\} \cup S$. Hence all $2^{n-2} - 1$ subsets $\{n\} \cup T$ in \mathbb{S} are reachable.

Altogether, $2^{n-1} + 2^{n-3} - 1$ subsets are reachable. It remains to be shown that all the reachable subsets are pairwise distinguishable. State 0 does not accept ab , while $n - 1$ accepts it. Each state i with $1 \leq i \leq n - 2$ accepts a^{n-1-i} and each of these words is accepted by only that one state, and n accepts b . So any two subsets S and $T \neq S$ are distinguishable. \square

Theorem 4. *For $n \geq 2$ there exists a quaternary star-free language L with $\kappa(L) = n$ such that $\kappa(L^*) = 2^{n-1} + 2^{n-2}$. For $n = 1$, the tight upper bound is 2.*

Proof. For $n = 1$, there are only two languages, \emptyset and Σ^* , and both are star-free. We have $\kappa(\emptyset^*) = 2$, and $\kappa((\Sigma^*)^*) = 1$. For $n = 2$, there are two star-free unary languages, ε and aa^* , and the bound cannot be met if $|\Sigma| = 1$. If $\Sigma = \{a, b\}$, then $b^*a\Sigma^*$ meets the bound 3. For $n = 3$, we analyzed all 3-state aperiodic automata using *GAP*. The bound 6 is met by $\mathcal{D}_3(a, b, c, d)$ defined above, and bounds 5 and 4 are met by $\mathcal{D}_3(a, b, c)$ and $\mathcal{D}_3(a, b)$, respectively. These bounds cannot be improved.

We now turn to the general case. We will show that the following sets of states are reachable in the nondeterministic automaton \mathcal{N} (see Fig. 4) from the initial state 0: the set $\{0\}$, all subsets of Q containing $\{1, n - 1\}$, and all non-empty subsets of $Q \setminus (n - 1)$. By Lemma 1, we can reach all these subsets by words in $\{a, b\}^*$, except $\{n\}$ and the subsets of $Q \setminus (n - 1)$ containing $\{1, n\}$.

We have $\{1, n - 1\} \xrightarrow{a} \{2, n\} \xrightarrow{c} \{1, n\}$; hence $\{1, n\}$ is reachable. Now consider $\{n\} \cup S$, where $S = \{s_1, s_2, \dots, s_k\} \in \mathbb{P}$. Let $h = n - 1 - s_k$; then using a^h we move to $\{1, n\} \cup S_{+h}$, and by c^h we reach $T = \{1, n\} \cup S$. Since $\{n\} \cup S$ is reachable by Lemma 1, T is also reachable. Thus we can reach all

the subsets of $Q \setminus (n-1)$ containing $\{1, n\}$ by words in $\{a, b, c\}^*$. The only set missing now is $\{n\}$, and it is reached by d .

In Lemma 1, we have already shown that any two subsets $S, T \subseteq Q$ such that $T \neq S$ are distinguishable by words in $\{a, b\}^*$. \square

Table 1 summarizes our results for the quotient complexity of L^* in case L is star-free. For unary languages, see Section 7. The figures in boldface type are known to be tight upper bounds. For $n = 4$, we analyzed all 4-state automata with non-decreasing input transformations. Automata $\mathcal{D}_4(a, b, c, d)$, $\mathcal{D}_4(a, b, c)$, and $\mathcal{D}_4(a, b)$ meet the bounds 12, 11, and 9, respectively. The bounds 11 and 9 cannot be improved in the class of automata with non-decreasing input transformations. For the rest, the bounds for $|\Sigma| = 3$ and $|\Sigma| = 2$ are met by $\mathcal{D}_n(a, b, c)$, and $\mathcal{D}_n(a, b)$, respectively.

Table 1: Quotient complexities for stars of star-free languages.

| n | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | ... | n |
|----------------|----------|----------|----------|-----------|-----------|-----------|-----------|------------|-----|---------------------------------------|
| $ \Sigma = 1$ | 2 | 2 | 3 | 4 | 5 | 7 | 13 | 21 | ... | $n^2 - 7n + 13$ |
| $ \Sigma = 2$ | – | 3 | 4 | 9 | 19 | 39 | 79 | 159 | ... | $2^{n-1} + 2^{n-3} - 1$ |
| $ \Sigma = 3$ | – | – | 5 | 11 | 23 | 47 | 95 | 191 | ... | $2^{n-1} + 2^{n-2} - 1$ |
| $ \Sigma = 4$ | – | – | 6 | 12 | 24 | 48 | 96 | 192 | ... | $2^{n-1} + 2^{n-2}$ |

6 Reversal

For regular binary languages, the tight bound for reversal [15] is 2^n . For star-free languages the bound $2^n - 1$ can be met, but with $|\Sigma| = n - 1$ letters.

Theorem 5. *For each $n \geq 1$ there exists a star-free language L with quotient complexity n such that $\kappa(L^R) = 2^n - 1$. The bound is met for $n = 1$ (respectively, for $n = 2$ and $n \geq 3$) with $|\Sigma| \geq 1$ (respectively, $|\Sigma| \geq 2$ and $|\Sigma| \geq n - 1$).*

Proof. For $n = 1$ and $\Sigma = \{a\}$, a^* is a witness. For $n = 2$ and $\Sigma = \{a, b\}$, Σ^*a is a witness. We have verified using *GAP* that all star-free languages L with $n = 2$ satisfy $\kappa(L^R) \leq 3$; hence this bound cannot be increased.

Now let $n \geq 3$, and let $\mathcal{D}_n = (Q, \Sigma, \delta, 1, E)$, where $Q = \{1, 2, \dots, n\}$, $\Sigma = \{a, b, c_3, \dots, c_{n-1}\}$, $E = \{i \in Q \mid i \text{ is even}\}$, and

$$\begin{aligned}
\delta(i, a) &= i + 1 \text{ for } i = 1, \dots, n - 1, & \delta(n, a) &= n, \\
\delta(i, b) &= i - 1 \text{ for } i = 2, \dots, n, & \delta(1, b) &= 1, \\
\delta(i, c_j) &= i \text{ for } i \neq j, & \delta(j, c_j) &= j - 1 \text{ for } j = 3, \dots, n - 1.
\end{aligned}$$

Since all the inputs perform non-decreasing transformations, \mathcal{D}_n is aperiodic. Figure 5 shows the NFA \mathcal{N} which is the reverse of DFA \mathcal{D}_7 .

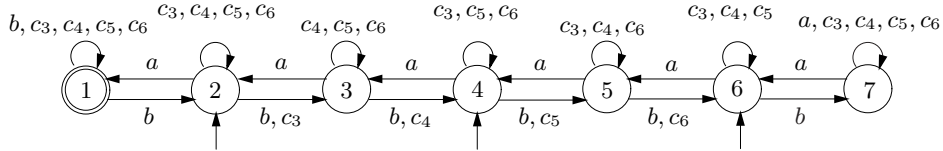


Figure 5: NFA \mathcal{N} of L^R , n odd.

Assume initially that n is odd. Let $S = \{s_1, \dots, s_k\}$ be a subset of Q , and let $1 \leq s_1 < \dots < s_k \leq n$. Then NFA \mathcal{N} has the following properties:

P1 If $3 \leq j \leq n-1$, $j \in S$ and $j-1 \notin S$, then input c_j deletes state j from S without changing any of the other states.

P2 If $3 \leq j \leq n-1$, $j \notin S$, and $j-1 \in S$, then input c_j adds state j to S without changing any of the other states.

We now examine the sets of reachable states in \mathcal{N} . The set O of all the odd states cannot be reached. For suppose that it is reached from some set S . If it is reached by a , then S must be a subset of $E \cup \{n\}$. However, the successor under a of such a set S also contains $n-1$ if it contains n . If we use b , then S must be a subset of $E \cup \{1\}$. But then the successor of S also contains 2 if it contains 1. If we use c_i with i odd, then S must be a subset of $O \setminus \{i\}$, and S must also have $i-1$. But then the successor of S also contains $i-1$, which is even, if it contains i . If we use c_i with i even, then we also get i .

If $n = 3$, there are no c_i inputs. Set $\{2\}$ is initial, $\{1\}$ can be reached by a and $\{3\}$ by b . We can get \emptyset by aa , $\{1, 2\}$ and $\{2, 3\}$ by ab and ba , respectively, and $\{1, 2, 3\}$ by abb . Set $\{1, 3\}$ is unreachable. So assume $n \geq 5$.

First, consider subsets S of M , the set of *middle states*; these are subsets of Q containing neither 1 nor n . If $2 \in S$ start with $E = \{2, 4, \dots, n-1\}$. By using inputs c_i , delete $n-1$ or not, add $n-2$ or not, etc., until we reach 2, which cannot be removed by any c_i . If $2 \notin S$, then $S_{-(s_1-2)}$ has 2, is a subset of M , and so is reachable; then S is reached by b^{s_1-2} from $S_{-(s_1-2)}$.

Second, consider subsets S of Q containing 1 but not n . If $2 \in S$, start with E and apply ab to reach $\{1\} \cup E$. Each state in E , except 2, is without a predecessor in $\{1\} \cup E$. Hence, by using inputs c_i , we can construct any such S . If $2 \notin S$, start with E and apply a to reach $O \setminus \{n\}$, where O of all the odd states. By using inputs c_i , we can construct any such set S .

Third, examine subsets S of Q containing n but not 1. If $2 \in S$, start with E and apply b to reach $E_{+1} = \{3, 5, \dots, n\} = O \setminus \{1\}$, and then apply a to get

$E \cup \{n\}$. Construct any such set S using inputs c_i . If $2 \notin S$, then S is a subset of $\{3, \dots, n\}$ containing n . Since the set S_{-1} is a subset of M , it is reachable; then S is reached by b from S_{-1} .

Finally, consider subsets S containing both 1 and n . Apply $baab$ to E to reach $\{1, n\} \cup E$. From this set we can reach any set containing $\{1, 2, n\}$.

Now assume that $2 \notin S$. We now show that $\{i\} \cup O$ is reachable for every even $i > 2$ in Q . Apply baa to E to reach $\{n-1\} \cup O$. If $i = n-1$, we are done; otherwise, delete $n-2$ and $n-1$ by c_{n-2} and c_{n-1} in that order. Then insert $n-3$ and $n-2$ by c_{n-3} and c_{n-2} in that order. If $i = n-3$, we are done; otherwise, continue in this fashion. If we reach $\{3, 4, 5\}$, then $i = 4$, and the process stops.

If $n = 5$, then we can reach $\{1, 3, 4, 5\}$. From $\{1, 3, 4, 5\}$ we can get $\{1, 5\}$, $\{1, 4, 5\}$, and $\{1, 3, 4, 5\}$. We are missing only $\{1, 3, 5\}$, which is unreachable.

If $n \geq 7$, from $\{n-1\} \cup O$ we can reach by c_i inputs all the subsets containing $\{1, n\}$ but not $\{2\}$, except those subsets containing $n-2$ without $n-1$. From now on, we are interested only in the missing subsets, which are with $\{1, n\}$, without 2, and have $n-2$ without $n-1$. Then take $\{n-3\} \cup O$. From here we can reach all subsets containing $\{1, n-2, n\}$ without $\{2, n-1\}$, except those containing $n-4$ without $n-3$. If $n = 7$, then $n-4 = 3$, and we are missing only $\{1, 3, 5, 7\}$, which is unreachable.

Continuing in this fashion, we can reach all the subsets containing $\{1, n\}$ but not 2, except O . Together with the case where $2 \in S$, we have all the states containing $\{1, n\}$, except O .

The case where n is even is similar [8]. □

7 Unary Languages

The case of unary languages is special. For regular unary languages, the tight bounds for each boolean operation $K \circ L$, product KL , star L^* , and reversal L^R are mn , mn , $n^2 - 2n + 2$, and n , respectively [21]. With the exception of the bound for reversal, these bounds cannot be met by star-free unary languages.

Theorem 6. *Let K and L be unary star-free languages with $\kappa(K) = m$ and $\kappa(L) = n$. The following bounds are tight:*

1. *For each boolean operation \circ , $\kappa(K \circ L) \leq \max(m, n)$.*
2. *For product, $\kappa(KL) \leq m + n - 1$.*
3. *For star, $\kappa(L^*) \leq 2$ if $n = 1$, $\kappa(L^*) \leq n$ if $2 \leq n \leq 5$, and $\kappa(L^*) \leq n^2 - 7n + 13$ otherwise.*

8 Conclusions

All the commonly used regular operations on star-free languages meet the quotient complexity bounds of arbitrary regular languages, except product for $n = 2$, reversal, and operations on unary languages.

References

- [1] Bassino, F., Giambruno, L., Nicaud, C.: Complexity of operations on cofinite languages. In López-Ortiz, A., ed.: Proceedings of the 9th Latin American Theoretical Informatics Symposium, (LATIN). Volume 6034 of LNCS, Springer (2010) 222–233
- [2] Bordin, H., Holzer, M., Kutrib, M.: Determination of finite automata accepting subregular languages. *Theoret. Comput. Sci.* **410** (2009) 3209–3249
- [3] Brzozowski, J.: Quotient complexity of regular languages. In Dassow, J., Pighizzini, G., Truthe, B., eds.: Proceedings of the 11th International Workshop on Descriptive Complexity of Formal Systems, Magdeburg, Germany, Otto-von-Guericke-Universität (2009) 25–42. (Extended abstract at <http://arxiv.org/abs/0907.4547>).
- [4] Brzozowski, J.: Complexity in convex languages. In Dediu, A.H., Fernau, H., Martin-Vide, C., eds.: Proceedings of the 4th International Conference on Language and Automata Theory (LATA). Volume 6031 of LNCS, Springer (2010) 1–15
- [5] Brzozowski, J., Jirásková, G., Li, B.: Quotient complexity of ideal languages. In López-Ortiz, A., ed.: Proceedings of the 9th Latin American Theoretical Informatics Symposium, (LATIN). Volume 6034 of LNCS, Springer (2010) 208–221
- [6] Brzozowski, J., Jirásková, G., Li, B., Smith, J.: Quotient complexity of bifix-, factor-, and subword-free languages. *These Proceedings* (2011)
- [7] Brzozowski, J., Jirásková, G., Zou, C.: Quotient complexity of closed languages. In Ablayev, F., Mayr, E.W., eds.: Proceedings of the 5th International Computer Science Symposium in Russia, (CSR). Volume 6072 of LNCS, Springer (2010) 84–95
- [8] Brzozowski, J., Liu, B.: Quotient complexity of star-free languages. <http://arxiv.org/abs/1012.3962> (December 2010)

- [9] Câmpeanu, C., Culik II, K., Salomaa, K., Yu, S.: State complexity of basic operations on finite languages. In Boldt, O., Jürgensen, H., eds.: Revised Papers from the 4th International Workshop on Automata Implementation, (WIA). Volume 2214 of LNCS, Springer (2001) 60–70
- [10] Cho, S., Huynh, D.T.: Finite-automaton aperiodicity is PSPACE-complete. *Theoret. Comput. Sci.* **88**(1) (1991) 99–116
- [11] GAP-Group: GAP - Groups, Algorithms, Programming - a System for Computational Discrete Algebra, <http://www.gap-system.org/> (2010)
- [12] Han, Y.S., Salomaa, K.: State complexity of basic operations on suffix-free regular languages. *Theoret. Comput. Sci.* **410**(27-29) (2009) 2537–2548
- [13] Han, Y.S., Salomaa, K., Wood, D.: Operational state complexity of prefix-free regular languages. In: Automata, Formal Languages, and Related Topics. (2009) 99–115
- [14] Holzer, M., Kutrib, M., Meckel, K.: Nondeterministic state complexity of star-free languages. In: Proceedings of the 16th International Conference on Implementation and Application of Automata (CIAA). Lecture Notes in Computer Science, Springer (2011) (To appear).
- [15] Leiss, E.: Succinct representation of regular languages by boolean automata. *Theoret. Comput. Sci.* **13** (2009) 323–330
- [16] Maslov, A.N.: Estimates of the number of states of finite automata. *Dokl. Akad. Nauk SSSR* **194** (1970) 1266–1268 (Russian). English translation: *Soviet Math. Dokl.* **11** (1970), 1373–1375.
- [17] McNaughton, R., Papert, S.: Counter-free automata. The MIT Press, Cambridge, MA (1971)
- [18] Pighizzini, G., Shallit, J.: Unary language operations, state complexity and Jacobsthal’s function. *Internat. J. Found. Comput. Sci.* **13** (2002) 145–159
- [19] Schützenberger, M.: On finite monoids having only trivial subgroups. *Inform. and Control* **8** (1965) 190–194
- [20] Yu, S.: State complexity of regular languages. *J. Autom. Lang. Comb.* **6** (2001) 221–234
- [21] Yu, S., Zhuang, Q., Salomaa, K.: The state complexities of some basic operations on regular languages. *Theoret. Comput. Sci.* **125**(2) (1994) 315–328