



ELSEVIER

Contents lists available at ScienceDirect

Journal of Algebra

www.elsevier.com/locate/jalgebra



Factoring formal maps into reversible or involutive factors ☆

Anthony G. O'Farrell^{a,*}, Dmitri Zaitsev^b

^a Department of Mathematics and Statistics, NUI, Maynooth, Co. Kildare, Ireland

^b School of Mathematics, Trinity College Dublin, Dublin 2, Ireland

ARTICLE INFO

Article history:

Received 6 March 2013

Available online 7 November 2013

Communicated by Michel Broué

MSC:

20E99

30D05

32A05

32H02

32H50

37F10

37F50

Keywords:

Involution

Reversible

Power series

Group

ABSTRACT

An element g of a group is called *reversible* if it is conjugate in the group to its inverse. An element is an *involution* if it is equal to its inverse. This paper is about factoring elements as products of reversibles in the group $\mathfrak{G}_n$ of formal maps of $(\mathbb{C}^n, 0)$, i.e. formally-invertible n -tuples of formal power series in n variables, with complex coefficients. The case $n = 1$ was already understood [25]. Each product F of reversibles has linear part $L(F)$ of determinant ± 1 . The main results are that for $n \geq 2$ each map F with $\det(L(F)) = \pm 1$ is the product of $2 + 3 \cdot \text{ceiling}(\log_2 n)$ reversibles, and may also be factored as the product of $9 + 6 \cdot \text{ceiling}(\log_2 n)$ involutions (where the ceiling of x is the smallest integer $\geq x$).

© 2013 Elsevier Inc. All rights reserved.

1. Introduction

1.1. It is an interesting fact that in many very large groups each element may be factored as the product of a small number of involutions. For instance, each permutation is the product of two involutions. Less trivially, Fine and Schweigert [11] showed that each homeomorphism of $\mathbb{R}$ onto itself is the composition of at most four involutions, each one conjugate to the map $x \mapsto -x$.

A natural generalization of an involution is a reversible. An element g of a group is called *reversible* if it is conjugate to its inverse, i.e. the conjugate $g^h := h^{-1}gh$ equals g^{-1} for some h from the group. We say that h *reverses* g or h is a *reverser of* g , in this case. Furthermore, if the reverser h can be

☆ Supported in part by the Science Foundation Ireland grant 10/RFP/MTH2878.

* Corresponding author.

E-mail addresses: anthonyg.ofarrell@gmail.com (A.G. O'Farrell), zaitsev@maths.tcd.ie (D. Zaitsev).

chosen to be an involution (i.e. an element of order at most 2), then g is called *strongly reversible*. (Note that some writers use the terminology “weakly reversible” and “reversible” instead of respectively “reversible” and “strongly reversible” used here. In finite group theory, the terms used are “real” and “strongly real”.) A strongly-reversible element is the product of two involutions. See [14–16]. If g is reversed by an element of finite even order $2k$, then g is the product of two elements of order $2k$. Indeed, it is easy to check that if g is reversed by some element h , then it factors as hf , where $h^2 = f^{-2}$, so if h has order $2k$, then so does f .

Reversible maps have their origin in problems of classical dynamics, such as the harmonic oscillator, the n -body problem or billiards, and Birkhoff [3] was one of the first to realize their significance. He observed that a Hamiltonian system with Hamiltonian quadratic in the momentum (such as the n -body problem), and other interesting dynamical systems admit what are called “time reversal symmetries”, i.e. transformations of the phase space that conjugate the dynamical system to its inverse.

In CR geometry reversible maps played important role in the celebrated work of Moser and Webster [23], arising as products of two involutions naturally associated to a CR singularity. Such a reversible map is called there “a discrete version of the Levi form” and plays a fundamental role in the proof of the convergence of the normal form for a CR singularity. More recently, this map has been used by Ahern and Gong [2] for so-called parabolic CR singularities.

The basic concept of reversible element makes sense in any group, and reversibility has been the focus of interest in many other application areas that involve some underlying group. For instance, reversible elements appear (sometimes under aliases) in connection with geometrical symmetries, special geodesics on Riemann surfaces, binary integral quadratic forms, quadratic correspondences, superposition of functions, approximation problems, toral automorphisms and foliations [7,8,10,12,24,28]. For further references to some contexts in which reversible elements have played a part, and a short survey of factorization results involving reversibles, see [26].

From the point of view of group theory, the subgroup $R^\infty(G)$ generated by the reversible elements of a group G is normal, and its isomorphism class is an isomorphism invariant of G . It has associated numerical invariants, which are very basic invariants of G , and their determination is a natural first step in the classification of G . One of these invariants is the supremum over all $g \in R^\infty(G)$ of the least number k of reversible factors r_j needed to represent g as a product $r_1 \cdots r_k$. In the language of Klopsch and Lev [21], this is the “diameter” of R^∞ with respect to the set $R(G)$ of reversibles.

The issue of factorization into reversibles (and involutions), and the number of factors needed has attracted attention in several group contexts — see for instance [1,4,5,9,13,17,19,22,29,30].

In this paper we consider the group $\mathfrak{G}_n$ of formally-invertible maps in $n \geq 2$ complex variables, and we discuss the factorization of a given map as a product of reversibles, and as a product of involutions. We get an explicit upper bound in terms of n for the above diameter, and also (when $n \geq 2$) for the (finite!) diameter of $R^\infty(\mathfrak{G}_n)$ with respect to the set of involutions.

In previous work the first author dealt with this problem for $n = 1$, and obtained the following results:

Theorem 1.1. (See [25].) *Let $F \in \mathfrak{G}_1$. Then the following are equivalent:*

- (1) F is a product of reversibles.
- (2) $F(z) = \pm z + O(z^2)$, i.e. $F(z) = \pm z + \text{terms in } z^2 \text{ and higher powers of } z$.
- (3) F is the product of two reversibles.

Theorem 1.2. (See [25].) *Let $F \in \mathfrak{G}_1$. Then the following are equivalent:*

- (1) F is a product of involutions.
- (2) For some $a \in \mathbb{C}$, $F(z) = \pm z + az^2 \pm a^2 z^3 + O(z^4)$.
- (3) F is the product of four involutions.

Thus not every reversible series in one variable is the product of a finite number of involutions. It depends upon the conjugacy class of the series, modulo z^4 . We shall see that the situation changes in higher dimensions.

In dimension 2, the authors previously showed the following:

Theorem 1.3. (See [27].) *If $F \in \mathfrak{G}_2$ has linear part of determinant 1, then it may be factorized as the product of 4 reversible elements.*

1.2. Results In this paper, we will show:

Theorem 1.4. *Let $n \geq 2$ and $F \in \mathfrak{G}_n$ have linear part of determinant 1. Let $c = \text{ceiling}(\log_2 n)$. Then*

- (1) *F is the product of $1 + 3c$ reversibles.*
- (2) *F is the product of $8 + 6c$ involutions.*

We also have:

Corollary 1.5. *Let $n \geq 2$ and $F \in \mathfrak{G}_n$. Let $c = \text{ceiling}(\log_2 n)$. Then the following are equivalent:*

- (1) *F is a product of reversibles.*
- (2) *The linear part of F has determinant ± 1 .*
- (3) *F is the product of $2 + 3c$ reversibles.*
- (4) *F is the product of $9 + 6c$ involutions.*
- (5) *F is the product of $3 + 6c$ involutions and two reversible maps of order dividing 4.*

Thus, for instance in dimension 2, every product of reversibles is also the product of at most 15 involutions.

1.3. Outline In Section 2 we define terminology and notation, and develop some tools that will be used in the proofs of these results. We identify some interesting subgroups of $\mathfrak{G}_n$, and construct homomorphisms connecting them. In particular, we identify a subgroup $\mathfrak{C}_n$, the centralizer in $\mathfrak{G}_n$ of a matrix subgroup $D_n \leq \text{GL}(n, \mathbb{C}) \leq \mathfrak{G}_n$, and we represent $\mathfrak{C}_n$ as the semidirect product of an abelian subgroup all of whose elements are reversible in $\mathfrak{G}_n$ and a subgroup (called $\mathfrak{R}_k$ or $\hat{\mathfrak{R}}_k$, depending on whether n is even or odd) of $\mathfrak{C}_k$, where k is roughly half of n . This structural information is summarized in the exact sequences shown in Fig. 1 on page 668. This allows us to carry out an induction, reducing the reversible factorization of elements of $\mathfrak{C}_n$ to the reversible factorization of k -dimensional maps, at the cost of one extra factor. Also, the subgroup $\mathfrak{C}_n$ has a representative of each so-called *generic* conjugacy class in $\mathfrak{G}_n$, and at the cost of an extra couple of factors, we can reduce the factorization of a general element of $\mathfrak{G}_n$ to the factorization of a generic element.

These subgroups and homomorphisms elaborate upon tools that were employed in our previous paper [27], in which we characterized the generic reversibles in dimension 2.

In considering involutive factors, we have to deal with the fact that not all one-dimensional maps $\chi \in \mathfrak{G}_1$ with multiplier 1 can be factored into involutions, so we have to find a way to factor the lift $H(\chi) \in \mathfrak{G}_2$ into involutions. Once we manage to do this, we can then start the induction at $n = 2$ and continue as before. This depends on the fact that the extra two or three reversible factors needed at each induction step are all *strongly reversible*, i.e. products of two involutions (see below).

In Section 3 we prove the two-dimensional results, and in Section 4 we prove the rest.

1.4. Open questions When we get into the detailed proofs, it will appear that for certain dimensions n we can derive estimates for the number of reversible factors needed that are considerably smaller than the estimate in Theorem 1.4. For instance, we can do much better with $n = 96$ than $n = 97$. See Section 4 and Table 1 for details.

But we do not know sharp values for the number of reversible or involutive factors needed in any case of dimension greater than 1. It may even be the case that a universal number of factors suffices in all dimensions. Also, it remains open, even for one-variable maps, whether results such as these hold for convergent power series. These are interesting problems.

One might wonder whether the coefficient field $\mathbb{C}$ may be replaced by another in these results. In our arguments, the properties of $\mathbb{C}$ that we use are the fact that it has characteristic zero and is algebraically-closed. We have not investigated more general fields. The paper [25] gave a complete account of reversibility and factorization into reversibles in the one-dimensional formal map group for arbitrary coefficient fields of characteristic zero. As far as we know, there is little known about reversibility when the characteristic of the coefficient field is finite. One should mention that, thanks to Klopsch [6, p. 16], [20] the involutions (and indeed the elements of finite order) have been identified for the so-called Nottingham groups (the one-dimensional case in which the coefficient field is finite), at least when the order of the field is odd.

2. Notation and preliminaries

2.1. Power series structures For $n \in \mathbb{N}$, let $\mathfrak{F}_n$ denote the ring of formal power series in n (commuting) variables, with complex coefficients, and let $\mathfrak{F}_n^\times$ denote the multiplicative group of its invertible elements, i.e. those with nonzero constant term, and let $\mathfrak{M}_n$ denote the complementary set $\mathfrak{F}_n \setminus \mathfrak{F}_n^\times$, the maximal ideal. Then an element of the set $\mathfrak{S}_n = (\mathfrak{M}_n)^n$ of n -tuples of elements of $\mathfrak{M}_n$ may be thought of as a formal map of $\mathbb{C}^n \rightarrow \mathbb{C}^n$, taking 0 to 0. Under formal composition, $\mathfrak{S}_n$ is a semigroup, with identity $\text{id}_n(z) = z$. Let $\mathfrak{G}_n \subset \mathfrak{S}_n$ be the group $\mathfrak{G}_n$ of formally-invertible elements.

We remark that $\mathfrak{G}_n$ is isomorphic to the group of $\mathbb{C}$ -algebra automorphisms of $\mathfrak{F}_n$. Indeed, if $g \in \mathfrak{G}_n$, then $f \mapsto f \circ g$ is an automorphism of $\mathfrak{F}_n$. Conversely, let Φ be any automorphism of $\mathfrak{F}_n$, and take $g = (\Phi(z_1), \dots, \Phi(z_n))$. Then Φ must map the unique maximal ideal $\mathfrak{M}_n$ onto itself, and hence determines an automorphism of each quotient $\mathfrak{F}_n/(\mathfrak{M}_n^k)$. Since (the cosets of) $z_1, \dots, z_n$ generate $\mathfrak{F}_n/(\mathfrak{M}_n^k)$, we have $\Phi(f) = f \circ g \bmod \mathfrak{M}_n^k$ for each f . Since this holds for each $k \in \mathbb{N}$, we conclude that Φ is just $f \mapsto f \circ g$.

2.2. The map L A typical element $F \in \mathfrak{S}_n$ takes the form

$$F(z) = (F_{,1}(z), \dots, F_{,n}(z)) = (F_{,1}(z_1, \dots, z_n), \dots, F_{,n}(z_1, \dots, z_n))$$

where each $F_{,j}(z)$ is a power series in n variables having complex coefficients, and no constant term. We shall refer to such series F as maps, even though they may be just ‘formal’, i.e. the series may fail to converge at any $z \neq 0$.

We usually write the formal composition of two maps $F, G \in \mathfrak{S}_n$ as FG . We also write the product of two complex numbers a and b as ab , but in cases where there might be some ambiguity we use $a \cdot b$. For n -tuples $a = (a_1, \dots, a_n)$ and $b = (b_1, \dots, b_n)$ (of various kinds) we also use $a \cdot b$ for the ‘dot’ product $a_1 \cdot b_1 + \dots + a_n \cdot b_n$, and, a little more unusually, we will use $a \times b$ for the *coordinatewise product*:

$$(a_1, \dots, a_n) \times (b_1, \dots, b_n) := (a_1 b_1, \dots, a_n b_n).$$

The series F may be expressed as a sum

$$F = \sum_{k=1}^{\infty} L_k(F),$$

where $L_k(F)$ is homogeneous of degree k . We abbreviate $L_1(F)$ to $L(F)$. This term, the *linear part of F* , belongs to the algebra of $n \times n$ matrices.

An element F of $\mathfrak{S}_n$ belongs to $\mathfrak{G}_n$ if and only if its linear part $L(F)$ belongs to the general linear group $\text{GL}(n, \mathbb{C})$.

We have the inclusion $\text{GL}(n, \mathbb{C}) \rightarrow \mathfrak{G}_n$, and $L : \mathfrak{G}_n \rightarrow \text{GL}(n, \mathbb{C})$ is a group homomorphism. We always identify $\text{GL}(n, \mathbb{C})$ with its image in $\mathfrak{G}_n$.

The elements of the kernel of L are said to be *tangent to the identity*.

2.3. Elements of finite order We note the following [27, Lemma 2.1]:

Lemma 2.1. *Let $n \in \mathbb{N}$ and let $\mathfrak{H}$ be a subgroup of $\mathfrak{G}_n$ such that*

- (1) $L(F) \in \mathfrak{H}$ whenever $F \in \mathfrak{H}$, and
- (2) $\mathfrak{H} \cap \ker L$ is closed under convex combinations, i.e. if $F_1, F_2 \in \mathfrak{H}$, $L(F_1) = L(F_2) = \text{id}$ and $0 < \alpha < 1$, then $\alpha F_1 + (1 - \alpha)F_2 \in \mathfrak{H}$.

Suppose $\Theta \in \mathfrak{H}$ has finite order. Then Θ is conjugated by an element of $\mathfrak{H} \cap \ker L$ to its linear part $L(\Theta)$.

This applies to $\mathfrak{H} = \mathfrak{G}_n$, $\mathfrak{G}_n \cap \ker L$, $\mathfrak{G}_n \cap \ker(\det \circ L) = L^{-1}(\text{SL}(n, \mathbb{C}))$ (and, more generally to $L^{-1}(H)$ for any subgroup $H \leq \text{GL}(n, \mathbb{C})$), to the corresponding subgroups of biholomorphic germs (i.e. series that converge on a neighborhood of the origin) and to other subgroups introduced below. It applies to the intersection of any two groups to which it applies.

In particular, in any $\mathfrak{H}$ to which the lemma applies, each involution is conjugate to one of the linear involutions in the group. In $\text{GL}(n, \mathbb{C})$, a matrix is an involution if and only if it is diagonalizable with eigenvalues ± 1 .

Thus the involutions in $\mathfrak{G}_n$ are all conjugate to their linear parts, which are involutions in $\text{GL}(n, \mathbb{C})$, and are classified up to conjugacy by the dimension of the eigenspace of the eigenvalue 1. Thus there are just n conjugacy classes of proper involutions, and condition (4) in Corollary 1.5 says that for $n \geq 3$ one may represent any such F as the product of at most $9 + 6 \cdot \text{ceiling}(\log_2 n)$ elements drawn from this small collection of classes.

We remark that there are also just a finite number of conjugacy classes in $\mathfrak{G}_n$ of maps of order dividing 4. The number is the number of ordered partitions of n as a sum of 4 nonnegative integers, which equals $\binom{n+3}{3}$.

2.4. Linear reversibles Reversibility is preserved by homomorphisms, so a map $F \in \mathfrak{G}_n$ is reversible only if $L(F)$ is reversible in $\text{GL}(n, \mathbb{C})$. Classification of linear reversible maps is simple. Suppose $F \in \text{GL}(n, \mathbb{C})$ is reversible. Since the Jordan normal form of F^{-1} consists of blocks of the same size as F with inverse eigenvalues, the eigenvalues of F that are not ± 1 must split into groups of pairs λ, λ^{-1} . Furthermore, we must have the same number of Jordan blocks of each size for λ as for λ^{-1} . Vice versa, if the eigenvalues of F are either ± 1 or split into groups of pairs λ, λ^{-1} with the same number of Jordan blocks of each size, then both F and F^{-1} have the same Jordan normal form and are therefore conjugate to each other.

2.5. The groups $D \leq \text{GL}(2, \mathbb{C})$ and $D_n \in \text{GL}(n, \mathbb{C})$ In particular, a linear map is reversible in $\text{GL}(2, \mathbb{C})$ if and only if it is an involution or is conjugate to $\begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix}$, $\begin{pmatrix} -1 & 1 \\ 0 & -1 \end{pmatrix}$ or to a matrix of the form

$$\tau_\mu = \begin{pmatrix} \mu & 0 \\ 0 & \mu^{-1} \end{pmatrix}, \quad (2.1)$$

for some $\mu \in \mathbb{C}^\times$. Thus each reversible $F \in \mathfrak{G}_2$ is conjugate in $\mathfrak{G}_2$ (by a linear conjugacy) to a map having one of these types as its linear part.

The collection of maps τ_μ , defined in (2.1) forms an abelian subgroup of $\mathfrak{G}_2$, which we denoted by D in [27]. The element (2.1) has infinite order precisely when μ is not a root of unity, and this is what we regarded as the generic situation when $n = 2$.

We now extend this notation to higher dimensions.

When $n = 2m \geq 2$ is even, we denote by D_n the set of maps $T \in \mathfrak{G}_n$ of the form

$$T(z) = (T_1(z_1, z_2), \dots, T_m(z_{n-1}, z_n)),$$

where each $T_j \in D$.

When $n = 2m + 1 \geq 3$ is odd, we denote by D_n the set of maps $T \in \mathfrak{G}_n$ of the form

$$T(z) = (T_1(z_1, z_2), \dots, T_m(z_{n-2}, z_{n-1}), z_n),$$

where each $T_j \in D$, i.e. $T = T' \times \text{id}_1$, where $T' \in D_{n-1}$ and id_1 is the identity map of $\mathbb{C}$.

In either case ($n = 2m$ or $n = 2m + 1$), D_n is a subgroup of $\mathfrak{G}_n$, isomorphic to the m -fold Cartesian product D^m .

An element $T \in D_n$ is called *generic* if the associated $T_j = \tau(\mu_j)$, where there is no “resonance” relation

$$\mu_1^{r_1} \cdots \mu_m^{r_m} = 1$$

with each $r_j \in \mathbb{Z}$, except the trivial relation with all $r_j = 0$. If T is generic, then in particular no μ_j is a root of unity. One could rephrase the condition as stating that the μ_j generate a free abelian subgroup of $\mathbb{C}^\times$ of rank m .

We shall make use of the classical Poincaré–Dulac Theorem [18, Section 4.8, Theorem 4.22], and we state it here in our language, for the reader's convenience:

Theorem 2.2 (Poincaré–Dulac). *Each map $F \in \mathfrak{G}_n$ is conjugate in $\mathfrak{G}_n$ to a map in the centralizer in $\mathfrak{G}_n$ of the linear part $L(F)$.*

In case $L(F)$ is a generic member of D_n we shall see shortly (cf. Lemma 2.3) that the centralizer of $L(F)$ in $\mathfrak{G}_n$ coincides with the centralizer of the whole subgroup D_n in $\mathfrak{G}_n$.

2.6. The group $\mathfrak{C}_n = C_{D_n}(\mathfrak{G}_n)$ In what follows, we shall usually have to distinguish odd and even $n \geq 2$. When $z \in \mathbb{C}^n$ with $n = 2m$ or $n = 2m + 1$, we define

$$p(z) = (z_1 z_2, \dots, z_{2m-1} z_{2m}),$$

and we set

$$\pi(z) := \begin{cases} p, & n = 2m, \\ (p, z_n), & n = 2m + 1. \end{cases}$$

Both p and π depend (implicitly) on n .

It is convenient, when dealing with $\mathfrak{G}_n$ for a given $n \geq 2$, to denote by k the number

$$k = \begin{cases} m, & n = 2m, \\ m + 1, & n = 2m + 1. \end{cases}$$

Thus m is the floor of $n/2$, and k is its ceiling. We shall assume this relation between n , m and k , always.

The map π sends $\mathbb{C}^n$ onto $\mathbb{C}^k$. A right inverse for π is the map $\epsilon = \epsilon_n : \mathbb{C}^k \rightarrow \mathbb{C}^n$, given by

$$\epsilon(t_1, \dots, t_m) = (t_1, 1, \dots, t_m, 1)$$

when $n = 2m$, and

$$\epsilon(t_1, \dots, t_m, t_k) = (t_1, 1, \dots, t_m, 1, t_k)$$

when $n = 2m + 1$.

We note, for future reference, that these maps preserve the coordinatewise product:

$$\pi(a \times b) = \pi(a) \times \pi(b), \quad \forall a, b \in \mathbb{C}^n$$

and

$$\epsilon(a \times b) = \epsilon(a) \times \epsilon(b), \quad \forall a, b \in \mathbb{C}^k.$$

Lemma 2.3. *Let $n \geq 2$, and $F \in \mathfrak{G}_n$. Then the following are equivalent:*

- (1) *F commutes with each element of D_n .*
- (2) *For some generic $\Lambda \in D_n$, F commutes with Λ .*
- (3) *If $n = 2m$ is even, then F takes the form*

$$F(z) = (z_1 \varphi_1(p), \dots, z_n \varphi_n(p)),$$

for some $\varphi_j \in \mathfrak{F}_m^\times$.

If $n = 2m + 1$ is odd, then F takes the form

$$F(z) = (z_1 \varphi_1(p, z_n), \dots, z_{2m} \varphi_{2m}(p, z_n), z_n \varphi_n(p, z_n) + p_1 \zeta_1(p) + \dots + p_m \zeta_m(p))$$

for some $\varphi_j \in \mathfrak{F}_{m+1}^\times$ and some $\zeta_k \in \mathfrak{F}_m$.

Proof. The only nontrivial implication is (2) $\implies$ (3).

Suppose (2) holds, and fix $F \in \mathfrak{G}_n$ commuting with some generic $\Lambda \in D_n$.

Case 1°: $n = 2m$, even. Then $\Lambda = \text{diag}(\lambda_1, 1/\lambda_1, \dots, \lambda_m, 1/\lambda_m)$, and there is no nontrivial resonance relation $\prod \lambda_j^{k_j} = 1$.

We may write $F_{1,1}$, the first component of F , in the form

$$z_1 \psi_1(z_1, \dots, z_n) + z_2 \psi_2(z_2, \dots, z_n) + \dots + z_n \psi_n(z_n),$$

where $\psi_j \in \mathfrak{F}_{n-j+1}$ (by gathering all monomial terms that involve z_1 into the term $z_1 \psi_1(z_1, \dots, z_n)$, all the terms that involve z_2 but not z_1 into the next, and so on). Equating the first components in the two sides of the equation $F\Lambda = \Lambda F$ gives

$$\begin{aligned} \lambda_1 z_1 \psi_1(\Lambda z) + \frac{z_2}{\lambda_1} \psi_2\left(\frac{z_2}{\lambda_1}, \lambda_2 z_3, \dots\right) + \dots + \frac{z_n}{\lambda_m} \psi_n\left(\frac{z_n}{\lambda_m}\right) \\ = \lambda_1 z_1 \psi_1(z_1, \dots, z_n) + \lambda_1 z_2 \psi_2 + \dots + \lambda_1 z_n \psi_n(z_n). \end{aligned}$$

Now, equating the coefficients of each monomial on the two sides, and using nonresonance, gives that $\psi_2 = \dots = \psi_n = 0$ and $\psi_1(\Lambda z) = \psi_1(z)$, so that $\psi_1(z)$ depends only on p . Thus the first component of F has the desired form.

A similar argument shows that each other component takes the form in (3), so (3) holds.

Case 2°: $n = 2m + 1$, odd. This time $\Lambda = \text{diag}(\lambda_1, 1/\lambda_1, \dots, \lambda_m, 1/\lambda_m, 1)$, and again there is no nontrivial resonance relation between the λ_j , $j = 1, \dots, m$.

Focusing, as before, on the first component in the identity $FA = \Lambda F$, we have

$$\begin{aligned} \lambda_1 z_1 \psi(\Lambda z) + \frac{z_2}{\lambda_1} \psi_2\left(\frac{z_2}{\lambda_1}, \lambda_2 z_3, \dots\right) + \dots + \frac{z_{2m}}{\lambda_m} \psi_n\left(\frac{z_{2m}}{\lambda_m}, z_n\right) + z_n \psi_n(z_n) \\ = \lambda_1 z_1 \psi_1(z_1, \dots, z_n) + \lambda_1 z_2 \psi_2 + \dots + \lambda_1 z_{2m} \psi_{2m}(z_{2m}, z_n) + \lambda_1 z_n \psi_n(z_n). \end{aligned}$$

Identifying terms, as before, we see that it proceeds just as in the even case (with z_n as an added parameter), for $\psi_1, \dots, \psi_{2m}$, and find that ψ_1 depends only on p and z_n , and that $\psi_2 = \dots = \psi_{2m} = 0$. Finally, $\psi_n(z_n) = 0$, since $\lambda_1 \neq 1$, so that the first component of F takes the desired form.

A similar argument looks after all the components except the last.

Writing $z = (z', z_n)$, with $z' \in \mathbb{C}^{2m}$, we may write the n -th component of F in the form

$$F_{,n}(z) = z' \cdot G(z') + z_n \psi_n(z),$$

where $\psi_n \in \mathfrak{F}_n$ and $G(z') \in (\mathfrak{F}_{2m})^{2m}$ is a $2m$ -vector of power series in $2m$ variables, and $\cdot$ here denotes the dot product. (This ψ_n is not the one used in the argument about the first component, the one that turned out to be zero.) The last component of the identity $FA = \Lambda F$ then yields

$$(\Lambda' z') \cdot G(\Lambda' z') + z_n \psi_n(\Lambda z) = z' \cdot G(z') + z_n \psi_n(z),$$

where Λ' denotes $\text{diag}(\lambda_1, 1/\lambda_1, \dots, \lambda_m, 1/\lambda_m)$. This tells us that $\psi_n(z)$ depends only on p and z_n , and that $z' \cdot G(z')$ depends only on p , and hence takes the form $p \cdot \zeta(p)$, for some m -tuple $\zeta \in (\mathfrak{F}_m)^m$. Thus (3) holds. $\square$

Remark 2.4. We note that by condition (3) of the lemma, each $F \in \mathfrak{C}_n$ has a diagonal linear part $L(F)$, because the terms $p \cdot \zeta(p)$ that occur in the odd case are at least quadratic, so that in all cases $L(F) = \text{diag}(\varphi_1(0), \dots, \varphi_n(0))$.

Definition 2.5. We denote by $\mathfrak{C}_n$ the group of all maps $F \in \mathfrak{G}_n$ that satisfy any of the equivalent conditions of Lemma 2.3.

2.7. The functions M , $\hat{M}$ and the involution J In terms of the coordinatewise product, in the even case $n = 2m$ we may represent the $F(z)$ in condition (3) of the lemma more compactly as $z \times \varphi(p)$. We also denote this map F by $M(\varphi)$. Thus $M = M_n$ is a bijection from $(\mathfrak{F}_m^\times)^{2m}$ onto $\mathfrak{C}_{2m}$. It is *not*, however, a homomorphism from the abelian product group structure of $(\mathfrak{F}_m^\times)^{2m}$.

For $n = 2m + 1$ odd, we note from the proof of the lemma that for $F \in \mathfrak{C}_n$, the last component $F(z)_{,n}$ takes the form $\psi(\pi(z)) = \psi(p, z_n)$, where $\psi \in \mathfrak{M}_k$ is completely unrestricted, except that it must have a nonzero coefficient on the monomial z_n . We denote the set of such ψ by $\hat{\mathfrak{M}}_k$, and we refer to them as *admissible* elements of $\mathfrak{M}_k$. Thus F takes the form

$$F(z) = (z_1 \varphi_1(p, z_n), \dots, z_{2m} \varphi_{2m}(p, z_n), \psi(p, z_n)),$$

with $\varphi \in (\mathfrak{F}_k^\times)^{2m}$ and $\psi \in \hat{\mathfrak{M}}_k$. We denote this F by $M_n(\varphi, \psi) = \hat{M}(\varphi, \psi)$. As before, $M_n = \hat{M}$ is a bijection from its domain onto $\mathfrak{C}_n$.

Denoting $j(z') = (z', 0)$ for $z' \in \mathbb{C}^{2m}$, we may write

$$\hat{M}(\varphi, \psi)(z', z_n) = j(z' \times \varphi(p, z_n)) + \psi(p, z_n) e_n,$$

where e_n denotes the last vector of the standard basis of $\mathbb{C}^n$.

Notice that M_n has a rather different kind of domain, depending on the parity of n .

We shall also use the notation J for the involutive element of $\mathfrak{G}_n$ defined by

$$J(z) = \begin{cases} (z_2, z_1, z_4, z_3, \dots, z_{2m}, z_{2m-1}), & n = 2m, \\ (z_2, z_1, z_4, z_3, \dots, z_{2m}, z_{2m-1}, z_n), & n = 2m + 1. \end{cases}$$

Observe that J reverses every $\Lambda \in D_n$, i.e. $J^{-1}\Lambda J = \Lambda^{-1}$.

2.8. The groups $\mathfrak{K}_m$ and $\hat{\mathfrak{K}}_k$ For $m \in \mathbb{N}$, we denote by $\mathfrak{K}_m$ the set of elements $F \in \mathfrak{G}_m$ that take the form

$$F(t) = (t_1\varphi_1(t), \dots, t_m\varphi_m(t)),$$

with each $\varphi_j \in \mathfrak{F}_m^\times$. One readily checks that $\mathfrak{K}_m$ is a subgroup of $\mathfrak{G}_m$.

We use the notation $N(\varphi) = N(\varphi_1, \dots, \varphi_m)$ to denote F of the above form. Using the coordinate-wise product, we also write $F(t) = t \times \varphi(t)$ and $N(\varphi) = \text{id}_m \times \varphi$.

For $k = m + 1$, we denote by $\hat{\mathfrak{K}}_k$ the set of elements $F \in \mathfrak{G}_k$ that (with $t = (t', t_k)$) take the form

$$F(t) = (t_1\varphi_1(t), \dots, t_m\varphi_m(t), t_k\varphi_k(t) + t' \cdot \zeta(t')),$$

with each $\varphi_j \in \mathfrak{F}_k^\times$ and $\zeta \in \mathfrak{F}_m$. We remark that every series $g(t) \in \mathfrak{M}_{m+1}$ with $g(0) = 0$ may be written in the form $t_k\varphi_k(t) + t' \cdot \zeta(t')$ for some $\varphi_k \in \mathfrak{F}_k$ and $\zeta \in \mathfrak{F}_m$, so that the form of the last component $F_{,k}$ is restricted only by the requirement that the coefficient of the monomial t_k be nonzero. This requirement is obviously needed for the invertibility of F . Thus $\hat{\mathfrak{K}}_k$ consists of the maps of the form

$$F(t) = (t_1\varphi_1(t), \dots, t_m\varphi_m(t), \psi(t)),$$

with $\varphi \in (\mathfrak{F}_k^\times)^m$ and $\psi \in \hat{\mathfrak{M}}_k$ (i.e. ψ admissible). It is routine to check that $\hat{\mathfrak{K}}_k$ is a subgroup of $\mathfrak{G}_k$.

We use the notation

$$\hat{N}(\varphi, \psi) = \hat{N}(\varphi_1, \dots, \varphi_k, \psi_1, \dots, \psi_m)$$

to denote F of the above form, and we may also write $F(t', t_k) = j(t' \times \varphi(t)) + \psi(t)e_k$ and $\hat{N}(\varphi, \psi) = j \circ (\text{id}_k \times \varphi) + \psi e_k$, where e_k stands for the vector $(0, \dots, 0, 1) \in \mathbb{C}^k$.

2.9. The homomorphisms P , H , and Φ If $n = 2m = 2k$ is even, then to $F = M(\varphi) \in \mathfrak{C}_n$ we associate the k variable map $P_n(F) \in \mathfrak{G}_k$ defined by

$$P(F)(t) = t \times \pi(\varphi(t)) = (t_1 \cdot \varphi_1(t) \cdot \varphi_2(t), \dots, t_m \cdot \varphi_{2m-1}(t) \cdot \varphi_{2m}(t)).$$

If $n = 2m + 1 = 2k - 1$ is odd, then to $F = \hat{M}(\varphi, \psi) \in \mathfrak{C}_n$ we associate the k variable map

$$P(F)(t) = (t', 1) \times \pi(\varphi(t), \psi(t)) = (t_1 \cdot \varphi_1(t) \cdot \varphi_2(t), \dots, t_m \cdot \varphi_{2m-1}(t) \cdot \varphi_{2m}(t), \psi(t)),$$

where $t = (t', t_k)$.

We have the basic semiconjugation property:

Lemma 2.6. For each $F \in \mathfrak{C}_n$, we have

$$P(F) \circ \pi = \pi \circ F. \quad (2.2)$$

Moreover, property (2.2) determines $P(F)$ uniquely.

Using the maps p and π , we may rewrite the definition of P as:

$$\begin{aligned} P(M(\varphi)) &= N(\pi \circ \varphi) = N(p \circ \varphi), \quad \text{if } n = 2m, \\ P(\hat{M}(\varphi, \psi)) &= \hat{N}(\pi \circ (\varphi, \psi)) = \hat{N}(p \circ \varphi, \psi), \quad \text{if } n = 2m + 1, \end{aligned} \quad (2.3)$$

where φ runs through $(\mathfrak{F}_k^\times)^{2m}$ and in the odd case ψ runs through $\hat{\mathfrak{M}}_k$.

Lemma 2.7. $P : \mathfrak{C}_n \rightarrow \mathfrak{G}_k$ is a group homomorphism.

Proof. This follows without further calculation from the uniqueness in (2.2) and the associativity of composition: If $F, G \in \mathfrak{C}$, then $P(F)P(G)\pi = P(F)\pi G = \pi FG$, so $P(FG) = P(F)P(G)$. $\square$

However, it is useful to note the explicit formulas for compositions of maps in the images of M and N , which are readily proved by direct calculation:

Lemma 2.8. Let φ, φ' and $\varphi'' \in (\mathfrak{F}_m^\times)^{2m}$. Let $\chi' = P(M(\varphi'))$. Then the following are equivalent:

- (1) $M(\varphi'') = M(\varphi)M(\varphi')$.
- (2) $\varphi''(t) = \varphi'(t) \times \varphi(\chi'(t))$.
- (3) $\varphi'' = \varphi' \times \varphi \circ (\text{id}_m \times \pi \circ \varphi')$.

Lemma 2.9. Let λ, λ' and $\lambda'' \in (\mathfrak{F}_m^\times)^m$. Let $\chi' = N(\lambda')$. Then the following are equivalent:

- (1) $N(\lambda'') = N(\lambda)N(\lambda')$.
- (2) $\lambda''(t) = \lambda'(t) \times \lambda(\chi'(t))$.
- (3) $\lambda'' = \lambda' \times \lambda \circ (\text{id}_m \times \lambda')$.

Similarly, for $\hat{M}$ and $\hat{N}$, we have:

Lemma 2.10. Let φ, φ' and $\varphi'' \in (\mathfrak{F}_{m+1}^\times)^{2m+1}$, and ψ, ψ' and $\psi'' \in \hat{\mathfrak{M}}_{m+1}$. Let $\chi' = P(\hat{M}(\varphi', \psi'))$. Then the following are equivalent:

- (1) $\hat{M}(\varphi'', \psi'') = \hat{M}(\varphi, \psi)\hat{M}(\varphi', \psi')$.
- (2) $\varphi''(t) = \varphi'(t) \times \varphi(\chi'(t))$ and $\psi''(t) = \psi(\chi'(t))$.
- (3) $\varphi'' = \varphi' \times \varphi \circ (\text{id}_m \times \pi \circ \varphi')$ and $\psi'' = \psi \circ \chi'$.

Lemma 2.11. Let λ, λ' and $\lambda'' \in (\mathfrak{F}_m^\times)^m$, and ψ, ψ' and $\psi'' \in \hat{\mathfrak{M}}_{m+1}$. Let $\chi' = \hat{N}(\varphi', \psi')$. Then the following are equivalent:

- (1) $\hat{N}(\lambda'', \psi'') = \hat{N}(\lambda, \psi)\hat{N}(\lambda', \psi')$.
- (2) $\lambda''(t) = \lambda'(t) \times \lambda(\chi'(t))$ and $\psi''(t) = \psi(\chi'(t))$.
- (3) $\lambda'' = \lambda' \times \lambda \circ (\text{id}_m \times \lambda')$ and $\psi'' = \psi \circ \chi'$.

The fact that P is a homomorphism is obtained again in the even case by precomposing π with the equation in part (3) of Lemma 2.8 and using $P(M(\varphi)) = \text{id}_m \times \pi \circ \varphi$. In fact, $\pi(a \times b) = \pi(a) \times \pi(b)$, so (3) gives

$$\pi \circ \varphi'' = (\pi \circ \varphi') \times (\pi \circ \varphi) \circ (\text{id}_m \times \pi \circ \varphi').$$

A similar argument applies in the odd case, using Lemmas 2.10 and 2.11.

The kernel of P is the set of maps F of the form

$$F(z) = \begin{cases} M(\varphi), & n = 2m = 2k, \\ M(\varphi, 1), & n = 2m + 1 = 2k - 1 \end{cases}$$

where $\varphi \in (\mathfrak{F}_k^\times)^{2m}$ and $\varphi_{2j-1}(t) = 1/\varphi_{2j}^{-1}(t)$ for $j = 1, \dots, m$. The group $\ker P$ is abelian.

For $n = 2m$, the map

$$\Phi : \begin{cases} (\mathfrak{F}_k^\times)^m \rightarrow \mathfrak{C}_n, \\ \varphi \mapsto M(\varphi_1, 1/\varphi_1, \dots, \varphi_m, 1/\varphi_m), \end{cases}$$

is a group isomorphism onto $\ker P$.

For $n = 2m + 1$, the corresponding isomorphism onto $\ker P$ is

$$\Phi : \begin{cases} (\mathfrak{F}_k^\times)^m \rightarrow \mathfrak{C}_n, \\ \varphi \mapsto M(\varphi_1, 1/\varphi_1, \dots, \varphi_m, 1/\varphi_m, 1). \end{cases}$$

Note that in each case the image of Φ consists of reversible elements. All are reversed by J .

Clearly, when $n = 2m$, the image of P lies in $\mathfrak{R}_m$, and when $n = 2m + 1$, the image lies in $\hat{\mathfrak{R}}_k$. To see that these are the exact images of P in the respective cases, we define right inverse maps:

For $n = 2m$, we define $H : \mathfrak{R}_m \rightarrow \mathfrak{C}_n$ by

$$H(N(\lambda))(z) = M(\epsilon \circ \lambda) = M(\lambda_1, 1, \lambda_2, 1, \dots, \lambda_m, 1). \quad (2.4)$$

From the definition of P , we see that $P(M(\varphi)) = N(\pi \circ \varphi)$ so obviously $P(H(N(\lambda))) = N(\pi \epsilon \lambda) = N(\lambda)$, as required.

(Moreover, for each $\chi \in \mathfrak{R}_m$, $H(\chi)$ is the unique element $F \in \mathfrak{C}_n$ with the properties $F(z)_{,j} = z_j$ for all even j and $F \circ \epsilon = \epsilon \circ \chi$.)

For $n = 2k - 1$, we define $H = H_n : \hat{\mathfrak{R}}_k \rightarrow \mathfrak{C}_n$ by

$$H(\hat{N}(\lambda, \psi))(z) = \hat{M}(\epsilon \circ (\lambda, \psi))(z) = \hat{M}(\lambda_1, 1, \lambda_2, 1, \dots, \lambda_m, 1, \psi)(z). \quad (2.5)$$

In this case, the definition of P amounts to

$$P(\hat{M}(\varphi, \psi)) = \hat{N}(p \circ \varphi, \psi),$$

so again $P(H(N(\lambda, \psi))) = N(\lambda, \psi)$, as required.

(Moreover, for each $\chi \in \hat{\mathfrak{R}}_k$, $H_n(\chi)$ is the unique element $F \in \mathfrak{C}_n$ with the properties $F(z)_{,j} = z_j$ for all even j and $F \circ \epsilon = \epsilon \circ \chi$.)

So we have proved:

Lemma 2.12. *The image of P is $\mathfrak{R}_m$ if $n = 2m$ and is $\hat{\mathfrak{R}}_k$ if $n = 2k - 1$.*

Next we have:

Lemma 2.13. *For each $n \geq 2$, H_n is a group homomorphism.*

$$\begin{array}{ccccccc}
 (1) & \rightarrow & (\mathfrak{F}_m^\times)^m & \xrightarrow{\Phi} & \mathfrak{C}_{2m} & \begin{array}{c} \xleftarrow{H} \\ \xrightarrow{P} \end{array} & \mathfrak{K}_m \rightarrow (1) \\
 & & & & \cap & & \cap \\
 & & & & \mathfrak{G}_{2m} & & \mathfrak{G}_m \\
 \\
 (1) & \rightarrow & (\mathfrak{F}_{m+1}^\times)^m & \xrightarrow{\Phi} & \mathfrak{C}_{2m+1} & \begin{array}{c} \xleftarrow{H} \\ \xrightarrow{P} \end{array} & \hat{\mathfrak{K}}_{m+1} \rightarrow (1) \\
 & & & & \cap & & \cap \\
 & & & & \mathfrak{G}_{2m+1} & & \mathfrak{G}_{m+1}
 \end{array}$$

Fig. 1. Exact sequences.

Proof. We give the explicit version, taking the cases separately.

1°: $n = 2m$. Fix two elements $\chi, \chi' \in \mathfrak{K}_m$, and let $\chi'' = \chi\chi'$. There are unique elements λ, λ' and $\lambda'' \in (\mathfrak{F}_m^\times)^m$ such that $\chi = N(\lambda)$, $\chi' = N(\lambda')$, and $\chi'' = N(\lambda'')$. By Lemma 2.8 and the definition of H , it suffices to show that

$$\epsilon \circ \lambda'' = \epsilon \circ \lambda' \times \epsilon \circ \lambda \circ (\text{id}_m \times \pi \circ \epsilon \circ \varphi').$$

But this is immediate from Lemma 2.9 and the fact that $\pi \circ \epsilon = \text{id}_m$.

2°: $n = 2m + 1$. Fix $\chi, \chi' \in \hat{\mathfrak{K}}_m$, and let $\chi'' = \chi\chi'$. There are unique elements λ, λ' and $\lambda'' \in (\mathfrak{F}_k^\times)^m$ and ψ, ψ' and $\psi'' \in \mathfrak{M}_k$ such that $\chi = \hat{N}(\lambda, \psi)$, $\chi' = \hat{N}(\lambda', \psi')$, and $\chi'' = \hat{N}(\lambda'', \psi'')$. By the definition of H , we have to show that

$$\hat{M}(\epsilon \circ \lambda'', \psi'') = \hat{M}(\epsilon \circ \lambda, \psi) \hat{M}(\epsilon \circ \lambda', \psi').$$

By Lemma 2.10, in view of the fact that

$$P(\hat{M}(\epsilon \circ \lambda', \psi')) = \hat{N}(\pi \circ \epsilon \circ (\lambda', \psi')) = \hat{N}(\lambda', \psi') = \chi',$$

this amounts to showing that

$$\epsilon \circ \lambda'' = \epsilon \circ \lambda' \times \epsilon \circ \lambda \circ \chi' \quad \text{and} \quad \psi'' = \psi \circ \chi'.$$

But this is immediate from Lemma 2.11. $\square$

Corollary 2.14. Let $n \geq 2$. The group $\mathfrak{C}_n$ is the semidirect product of $\text{im } \Phi$ and $\text{im } H$. Each $F \in \mathfrak{C}_n$ has a unique factorization in the form $H(\chi)\Phi(\varphi)$, with $\chi \in \text{im } P$ and $\varphi \in (\mathfrak{F}_k^\times)^m$.

Proof. This follows from the facts that $\text{im } \Phi = \ker P$ is normal and that the homomorphism H is a right inverse for P . $\square$

However, $\mathfrak{C}_n$ is not the direct product of $\text{im } H$ and $\text{im } \Phi$.

The structural results of this subsection are summarized in Fig. 1.

3. Proof of Theorem 1.4 in dimension 2

The case $n = 2$ of our main theorem serves as the foundation layer for an inductive proof of the general case, and now we lay this down.

For the reader's convenience, we include the short proof of our previously-published Theorem 1.3 (which is the same as part (1) of Theorem 1.4 in case $n = 2$).

Proof. Let $F \in \mathfrak{G}_2$ have $\det L(F) = 1$. We have to show that F may be factorized as $F = g_1 g_2 g_3 g_4$, where each g_j is reversible in $\mathfrak{G}$.

In fact, if $\det L(F) = 1$, then multiplying by some (reversible) $\Lambda \in D$ (possibly the identity) we can arrange that $L(F\Lambda)$ is conjugate to an infinite-order element of D . Then by the Poincaré–Dulac Theorem, $F\Lambda$ is conjugate (say by $K \in \mathfrak{G}$) to some element of $\mathfrak{C}$, so $(F\Lambda)^K$ may be factored as $H(\chi)\Phi(\varphi)$, where $\chi(t) = t + \text{HOT}$. Now $\Phi(\varphi)$ is reversible, and we know [25, Theorem 9(2)] that χ is the product of two reversibles in $\mathfrak{G}_1$, so $H(\chi)$ is the product of two reversibles, say $H(\chi_1)$ and $H(\chi_2)$. Thus

$$F^K = H(\chi_1)H(\chi_2)\Phi(\varphi)(\Lambda^{-1})^K$$

is the product of four reversibles, and conjugating with K^{-1} we obtain the result. $\square$

Proof of Theorem 1.4, part (2) when $n = 2$. Let $F \in \mathfrak{G}_2$ with $\det L(F) = +1$. With the notation in the last proof, Λ^K and $\Phi(\varphi)$ are strongly reversible, since Λ and $\Phi(\varphi)$ are reversed by the involution J . Thus it suffices to prove that $H(\chi)$ is the product of 10 involutions, whenever $\chi(t) = t + \text{HOT} \in \mathfrak{G}_1$.

Now we may factor χ as $\chi_1 \chi_2$, where these take the form

$$\begin{aligned}\chi_1(t) &= t + \alpha t^2 + \alpha^2 t^3, \\ \chi_2(t) &= t + \beta t^3 + \text{HOT}\end{aligned}$$

(possibly with $\alpha = 0$ or $\beta = 0$). The map χ_1 is the identity or is conjugate to the map f_1 , given by (cf. [25])

$$f_1(t) = \frac{t}{1-t} = t + t^2 + t^3 + t^4 + \text{HOT}, \quad (3.1)$$

reversed by $t \mapsto -t$, hence is the product of two involutions in $\mathfrak{G}_1$, and hence so is $H(\chi_1)$. Thus, since $H(\chi) = H(\chi_1)H(\chi_2)$, it suffices to show that $S = H(\chi_2)$ is the product of 8 involutions.

If $\beta = 0$, then χ_2 is the product of 4 involutions in view of [25, Theorem 9], so we consider the case $\beta \neq 0$. By a conjugation in $\mathfrak{G}_1$, we may take $\beta = 1$, so S takes the form

$$S(z) = (z_1(1 + p^2 + \text{HOT}), z_2).$$

Take the map

$$T = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \in \text{SL}(2, \mathbb{C}).$$

A calculation yields that, up to terms of degree 5,

$$T^{-1}ST(z) = \begin{pmatrix} d & -b \\ -c & a \end{pmatrix} \begin{pmatrix} 1+A & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} az_1 + bz_2 \\ cz_1 + dz_2 \end{pmatrix} = \begin{pmatrix} z_1 + dB \\ z_2 - cB \end{pmatrix},$$

where $\det T = 1$, $A = (az_1 + bz_2)^2(cz_1 + dz_2)^2$ and $B = (az_1 + bz_2)^3(cz_1 + dz_2)^2$.

Let $\Lambda_1 = \begin{pmatrix} 2 & 0 \\ 0 & \frac{1}{2} \end{pmatrix}$. Then $\Lambda_1 T^{-1}ST$ equals

$$\left(2z_1(1 + ad(a^2d^2 + 6abcd + 3b^2c^2)p^2), \frac{1}{2}z_2(1 - bc(b^2c^2 + 6abcd + 3a^2d^2)p^2) \right) \quad (3.2)$$

plus non-resonant terms of order 5. By the Poincaré–Dulac Theorem, $\Lambda_1 T^{-1} S T$ is conjugate to the map S_1 obtained by removing all non-resonant terms. A calculation shows that S_1 equals (3.2) up to terms of degree 5 in z . We now choose T such that

$$ad(a^2d^2 + 6abcd + 3b^2c^2) = bc(b^2c^2 + 6abcd + 3a^2d^2), \quad (3.3)$$

or, substituting $ad = bc + 1$,

$$(bc + 1)((bc + 1)^2 + 6bc(bc + 1) + 3b^2c^2) = bc(b^2c^2 + 6bc(bc + 1) + 3(bc + 1)^2), \quad (3.4)$$

which simplifies to

$$6b^2c^2 + 6bc + 1 = 0 \quad (3.5)$$

and clearly has a solution.

Then $S_1(z)$ factors as $H(\chi)\Phi(\varphi)$ with $\chi(t) = P(S_1)(t) = t + O(t^4)$. Hence by [25, Theorem 9], χ and therefore $H(\chi)$ is the product of four involutions. Thus S_1 is the product of 6 involutions. Thus $\Lambda_1 T^{-1} S T$ is the product of 6 involutions, so S is the product of 8. This concludes the proof. $\square$

Each product $F = f_1 \cdots f_n$ of reversible f_j 's has $\det L(F) = \pm 1$, so (multiplying if necessary by a suitable linear involution) it follows from Theorem 1.3 that each product of reversibles reduces to the product of five. It also follows that the elements that are products of reversibles are precisely those with $\det L(F) = \pm 1$. Thus the case $n = 2$ of Corollary 1.5 is immediate.

4. Proof of Theorem 1.4 in dimension $n > 2$

We will actually prove a more refined result, in which the number of factors required depends in a more complicated way on the dimension n .

First, we introduce notation for the number of factors needed, in various situations:

For $n \geq 2$, let $r_1(n)$ denote the least $r \in \mathbb{N}$ such that each $F \in \mathfrak{G}_n$ having $\det L(F) = 1$ may be expressed as the product of r reversible elements of $\mathfrak{G}_n$. Similarly, let $r_d(n)$ be the least number of reversible factors from $\mathfrak{G}_n$ required for the factorization of each $F \in \mathfrak{G}_n$ having $L(F) \in D_n$. Finally, let $r_c(n)$ be the least number of reversible factors from $\mathfrak{G}_n$ required for the factorization of each $F \in \mathfrak{C}_n$ having $L(F) \in D_n$.

It is obvious that

$$r_c(n) \leq r_d(n) \leq r_1(n) \quad (4.1)$$

whenever $n \geq 2$.

Lemma 4.1. *Let $n \geq 2$. Each diagonal matrix $T \in \mathrm{SL}(n, \mathbb{C})$ may be factored as the product of two diagonal matrices $T_1 T_2$, where $T_1 \in D_n$ and there is a permutation matrix σ such that the conjugate T_2^σ belongs to D_n .*

Proof. Let $T = \mathrm{diag}(\lambda_1, \lambda_2, \dots, \lambda_n)$, and note that $\lambda_1 \cdots \lambda_n = 1$.

Take

$$T_1 = \mathrm{diag}(\lambda_1, 1/\lambda_1, \lambda_1 \lambda_2 \lambda_3, 1/(\lambda_1 \lambda_2 \lambda_3), \dots),$$

and

$$T_2 = \mathrm{diag}(1, \lambda_1 \lambda_2, 1/(\lambda_1 \lambda_2), \lambda_1 \lambda_2 \lambda_3 \lambda_4, 1/(\lambda_1 \lambda_2 \lambda_3 \lambda_4), \dots).$$

If n is odd, then the last entry in T_1 is 1, so $T_1 \in D_n$. Since T_2 is conjugated into D_n by the permutation $(1n)$ that swaps the coordinates z_1 and z_n , we are done, in this case.

If n is even, then $T_1 \in D_n$, and T_2 has both first and last entries equal to 1, so it is conjugated into D_n by the n -cycle $(12 \dots n)$ that rotates the last coordinate back into first position, and shifts the others down. $\square$

Lemma 4.2. *Each element of D_n may be factored as the product of two generic elements of D_n .*

Proof. Let $T \in D_n$. Then $T = \Phi(\alpha)$ for some $\alpha \in (\mathbb{C}^\times)^m$. Choose $\lambda \in (\mathbb{C}^\times)^m$ such that λ_j is multiplicatively independent of $\alpha_1, \dots, \alpha_m, \lambda_1, \dots, \lambda_{j-1}$, for each j . Take $T_1 = \Phi(\alpha \times \lambda)$ and $T_2 = \Phi(\lambda_1^{-1}, \dots, \lambda_m^{-1})$. Then each T_j is a generic element of D_n , and $T = T_1 T_2$. $\square$

Lemma 4.3. *Let $n \geq 2$. Each diagonal matrix $T \in \mathrm{SL}(n, \mathbb{C})$ may be factored as the product of three diagonal matrices $T_1 T_2 T_3$, where $T_1 \in D_n$ and there is a permutation matrix σ such that the conjugates T_2^σ and T_3^σ belong to D_n , and T_3^σ is a generic element.*

Proof. Let $T_1 T_2'$ be the factorization and σ the permutation given by Lemma 4.1, and apply Lemma 4.2 to $(T_2')^\sigma$. $\square$

Lemma 4.4. *Let $n \geq 3$. Then $r_1(n) \leq r_c(n) + 2$.*

Proof. Fix $F \in \mathfrak{G}_n$ with $\det L(F) = 1$.

By using a linear conjugation, if need be, we may assume that $L(F)$ is in Jordan canonical form, so that the diagonal elements multiply to 1.

Write $L(F) = T + N$, where T is diagonal and N is strictly upper triangular. Applying the last lemma, we can write $T = T_1 T_2 T_3$, where $T_1 \in D_n$ and both T_2 and T_3 are diagonal, and conjugate by the same permutation σ of coordinates to elements of D_n , with T_3^σ generic. Let $F_1 = (T_1 T_2)^{-1} F$. Then $L(F_1)$ is upper triangular, with the same diagonal as T_3 .

The eigenvalues of $L(F_1)$ are its diagonal elements, and are distinct, so we may conjugate $L(F_1)$ to T_3 by using an element of $\mathrm{GL}(n, \mathbb{C})$. Applying the same conjugation to F_1 , we conjugate F_1 to a map F_2 with $L(F_2) = T_3$. Applying the Poincaré–Dulac Theorem, we can conjugate F_2 to a map F_3 that commutes with T_3 , without changing the linear part, so $L(F_3) = T_3$. Then F_3^σ commutes with T_3^σ , and hence belongs to $\mathfrak{C}_n$, and has $L(F_3^\sigma) = T_3^\sigma$.

Now F_3^σ is the product of $r_c(n)$ reversibles, hence so are F_3 , F_2 and F_1 . Since T_1 and T_2 are reversible, F is the product of $2 + r_c(n)$ reversibles. $\square$

Lemma 4.5. *Let $n \geq 3$. Then $r_d(n) \leq r_c(n) + 1$.*

Proof. Fix $F \in \mathfrak{G}_n$ with $L(F) \in D_n$. By Lemma 4.2, we may factor $L(F) = T_1 T_2$, where each $T_j \in D_n$ is generic. Taking $F_1 = T_1^{-1} F$, we have $L(F_1) = T_2$, and applying the Poincaré–Dulac Theorem we can conjugate F_1 to an element F_2 of $\mathfrak{C}_n$ having $L(F_2) = T_2$. Since F_2 is the product of $r_c(n)$ reversibles, so is F_1 , and hence $F = T_1 F_1$ is the product of $1 + r_c(n)$. $\square$

Lemma 4.6. *Let $m \geq 1$. Then*

- (1) $r_c(2m) \leq 1 + r_d(m)$, and
- (2) $r_c(2m+1) \leq 1 + r_1(m+1)$.

Proof. (1) Let $n = 2m$. Fix $F \in \mathfrak{C}_n$, with $L(F) \in D_n$. Then $\chi = P(F_1)$ belongs to $\mathfrak{G}_m$ and is tangent to the identity, so it may be factored as the product of $r_d(m)$ reversibles.

By Corollary 2.14, we can factor F as $H(\chi)\Phi(\varphi)$, for some $\varphi \in (\mathfrak{F}_m^\times)^m$, and we know that $\Phi(\varphi)$ is reversed by J , so F is the product of $1 + r_d(m)$ reversibles. Thus $r_c(n) \leq 1 + r_d(m)$.

(2) Let $n = 2m + 1 = 2k - 1$. Fix $F \in \mathfrak{C}_n$, with $L(F) \in D_n$. Then this time $\chi = P(F_1) \in \mathfrak{G}_k$ may fail to be tangent to the identity, or even to belong to D_k , but still has $\det L(\chi) = 1$, so it may be factored as the product of $r_1(k)$ reversibles. Proceeding as before, we get $r_c(n) \leq 1 + r_1(k)$, as required. $\square$

Corollary 4.7. *If $n \geq 2$, then $r_1(n) \leq 1 + 3 \cdot \text{ceiling}(\log_2 n)$.*

Proof. We proceed inductively, starting at $n = 2$.

For $n = 2$, [Theorem 1.3](#) tells us that $r_1(n) \leq 4 = 1 + 3 \cdot \text{ceiling}(\log_2 n)$.

Fix $n > 2$, and assume that for every $n' < n$, we have $r_1(n') \leq 1 + 3 \cdot \text{ceiling}(\log_2 n')$.

Then with k as usual, [Lemmas 4.4 and 4.6](#) and inequalities [\(4.1\)](#) yield

$$r_1(n) \leq 2 + r_c(n) \leq 3 + r_1(k) \leq 4 + 3 \cdot \text{ceiling}(\log_2 k)$$

so, since $\text{ceiling}(\log_2 k)$ is one less than $\text{ceiling}(\log_2 n)$, we have $r_1(n) \leq 1 + 3 \cdot \text{ceiling}(\log_2 n)$, and the induction step is complete. $\square$

This corollary has the same content as [Theorem 1.4](#), part (1), so that is now proven.

Proof of Theorem 1.4, part (2). Denote the minimal number of involutive factors needed to express each member of the classes corresponding to r_1 , r_d and r_c , respectively, by i_1 , i_d and i_c , respectively. Observing that the elements of D_n and of $\text{im } \Phi$ are strongly reversible, and reviewing the proofs of [Lemmas 4.4 and 4.6](#), we obtain the following estimates:

$$i_c(n) \leq i_d(n) \leq i_1(n),$$

$$i_1(n) \leq i_c(n) + 4,$$

$$i_d(n) \leq i_c(n) + 2,$$

$$i_c(2m) \leq 2 + i_d(m),$$

$$i_c(2m + 1) \leq 2 + i_1(m + 1),$$

whenever $m, n \in \mathbb{N}$ and the terms on both sides are defined (i.e. we say nothing about $i_1(1)$, $i_d(1)$ or $i_c(1)$). We can now carry out an induction to estimate $c_1(n)$, and each induction step adds 6 to the number of involutions that will suffice.

At the lowest level, when $n = 2$, [Theorem 1.3](#) part (2) tells us that $14 = 8 + 6 \cdot \text{ceiling}(\log_2 n)$ involutions suffice, so induction gives the result, since $\text{ceiling}(\log_2 n)$ increases by 1 at each step. $\square$

Proof of Corollary 1.5. The equivalence of (1), (2) and (3) follows from the theorem and the fact that each reversible, and hence each product of reversibles has determinant ± 1 .

Closer analysis of the proof of the theorem given above reveals that each F with $\det L(F) = 1$ may also be represented as the product of $6 \cdot \text{ceiling}(\log_2 n)$ involutions and one special map that is a homomorphic image of an element $\chi \in \mathfrak{G}_1$ having multiplier $+1$. (The homomorphism is the composition of repeated H and inner automorphisms.) Examining the detail in the proof of [Theorem 1.1](#), one finds that χ is the product of two reversibles, one strongly reversible, and the other reversed by an element of order dividing 4. (The theorem is Theorem 9 of [\[25\]](#), and the proof is on pp. 18–19 of that paper. The map is denoted f , instead of χ . Three cases are considered. In case 1° , f is factored as gh , where g is conjugate to $z + z^2 + z^3$, which is strongly reversible, and h is id or is conjugate to $z + z^3 + \frac{3}{2}z^5$, which is reversed by $z \mapsto iz$. In case 2° – note that there is a misprint: this case is $p > 2$, not $p \geq 2$ – f is the product of two maps conjugate to $z + z^2 + z^3$. Finally, in case 3° , $f = gh$, where g is conjugate to the aforementioned $z + z^3 + \frac{3}{2}z^5$ and h is conjugate to $z + z^4 + 2z^7$, and

Table 1
Bounds for the number of reversible factors.

n	$r_1(n)$	$r_d(n)$	$r_c(n)$	n	$r_1(n)$	$r_d(n)$	$r_c(n)$
1	2	2	2	9	13	12	11
2	4	4	3	10	12	11	10
3	7	6	5	11	12	11	10
4	7	6	5	12	11	10	9
5	10	9	8	13	13	12	11
6	9	8	7	14	12	11	10
7	10	9	8	15	12	11	10
8	9	8	7	16	11	10	9

hence is strongly reversible.) Thus χ , and hence the special map, are each the product of two involutions and two reversible maps of degree dividing 4, so that F is the product of $2 + 6 \cdot \text{ceiling}(\log_2 n)$ involutions and two reversible maps of degree dividing 4. $\square$

Remark 4.8. The inequalities in Lemmas 4.4 and 4.6 may be used to derive estimates for $r_1(n)$ that are often considerably smaller than the estimate $1 + 3 \cdot \text{ceiling}(\log_2 n)$. These estimates depend on the parity of the terms in the chain of links $n' \rightarrow k'$ connecting n to 2. For instance, from the chain

$$96 \rightarrow 48 \rightarrow 24 \rightarrow 12 \rightarrow 6 \rightarrow 3 \rightarrow 2$$

one obtains $r_1(96) \leq 14$, in contrast to the estimate $r_1(97) \leq 20$ obtained from the chain

$$97 \rightarrow 49 \rightarrow 25 \rightarrow 13 \rightarrow 7 \rightarrow 4 \rightarrow 2.$$

The best estimates are obtained for powers of 2:

$$c_1(2^n) \leq 2 + 2n.$$

Table 1 gives the best estimates obtainable from these lemmas for the first few n .

We do not know sharp values for $r_1(n)$ or $r_d(n)$, in any case of dimension greater than 1.

References

- [1] P. Ahern, A.G. O'Farrell, Reversible biholomorphic germs, *Comput. Methods Funct. Theory* 9 (2009) 473–484.
- [2] P. Ahern, X. Gong, A complete classification for pairs of real analytic curves in the complex plane with tangential intersection, *J. Dyn. Control Syst.* 11 (2005) 1–71.
- [3] G.D. Birkhoff, The restricted problem of three bodies, *Rend. Circ. Mat. Palermo* 39 (1915) 265–334.
- [4] F. Bracci, D. Zaitsev, Dynamics of one-resonant biholomorphisms, *J. Eur. Math. Soc.* 15 (1) (2013) 179–200.
- [5] T.E. Brendle, B. Farb, Every mapping class group is generated by 6 involutions, *J. Algebra* 278 (2004) 187–198.
- [6] R. Camina, The Nottingham group, in: *New Horizons in pro- p Groups*, in: *Progr. Math.*, vol. 184, 2000, pp. 205–221.
- [7] D.Ž. Djoković, Product of two involutions, *Arch. Math. (Basel)* 18 (1967) 582–584.
- [8] D.Ž. Djoković, Pairs of involutions in the general linear group, *J. Algebra* 100 (1986) 214–223.
- [9] E.W. Ellers, The reflection length of a transformation in the unitary group over a finite field, *Linear Multilinear Algebra* 35 (1993) 11–35.
- [10] W. Feit, G.J. Zuckerman, Reality properties of conjugacy classes in spin groups and symplectic groups, *Contemp. Math.* 13 (1982) 239–253.
- [11] N.J. Fine, G.E. Schweigert, On the group of homeomorphisms of an arc, *Ann. of Math.* 62 (2) (1955) 237–253.
- [12] É. Ghys, V. Sergiescu, Stabilité et conjugaison différentiable pour certains feuilletages, *Topology* 19 (1980) 179–197.
- [13] X. Gong, Anti-holomorphically reversible holomorphic maps that are not holomorphically reversible, in: *Geometric Function Theory in Several Complex Variables*, World Scientific Publishing, River Edge, NJ, 2004, pp. 151–164.
- [14] R. Gow, Real-valued characters and the Schur index, *J. Algebra* 40 (1976) 258–270.
- [15] R. Gow, Real-valued and 2-rational group characters, *J. Algebra* 61 (2) (1979) 388–413.
- [16] R. Gow, Products of two involutions in classical groups of characteristic 2, *J. Algebra* 71 (1981) 583–591.
- [17] W.H. Gustafson, P.R. Halmos, H. Radjavi, Products of involutions, *Linear Algebra Appl.* 13 (1976) 157–162.
- [18] Yu. Ilyashenko, S. Yakovenko, *Lectures on Analytic Differential Equations*, AMS, Providence, ISBN 978-0-8218-3667-5, 2008.

- [19] H. Ishibashi, Involutive expressions for elements in $GL_n(\mathbb{Z})$ and $SL_n(\mathbb{Z})$, *Linear Algebra Appl.* 219 (1995) 165–177.
- [20] B. Klopsch, Automorphisms of the Nottingham group, *J. Algebra* 223 (2000) 37–56.
- [21] B. Klopsch, V. Lev, How long does it take to generate a group?, *J. Algebra* 261 (2003) 145–171.
- [22] F. Knüppel, K. Nielsen, Products of involutions in $O^+(V)$, *Linear Algebra Appl.* 94 (1987) 217–222.
- [23] J.K. Moser, S.M. Webster, Normal forms for real surfaces in $\mathbb{C}^2$ near complex tangents and hyperbolic surface transformations, *Acta Math.* 150 (3–4) (1983) 255–296.
- [24] K. Nielsen, On bireflectionality and trireflectionality of orthogonal groups, *Linear Algebra Appl.* 94 (1987) 197–208.
- [25] A.G. O'Farrell, Compositions of involutive power series and reversible series, *Comput. Methods Funct. Theory* 8 (2008) 173–193.
- [26] A.G. O'Farrell, Reversibility questions in groups arising in analysis, *CRM Proc. Lect. Notes* 55 (2012) 293–300.
- [27] A.G. O'Farrell, D. Zaitsev, Formally reversible maps of $(\mathbb{C}^2, 0)$, *Ann. Sc. Norm. Super. Pisa* (2013), http://dx.doi.org/10.2422/2036-2145.201201_001, in press, arXiv:1111.6984.
- [28] P. Sarnak, Reciprocal geodesics, *Clay Math. Proc.* 7 (2007) 217–237.
- [29] A. Stein, $1\frac{1}{2}$ -generation of finite simple groups, *Beiträge Algebra Geom.* 39 (1998) 349–358.
- [30] S.M. Webster, Pairs of intersecting real manifolds in complex space, *Asian J. Math.* 7 (4) (2003) 449–462.