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Power linear Keller maps with ditto
triangularizations

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Abstract
We show that power linear Keller maps 
\[ F = \left( x_1 + (A_1x)^d, x_2 + (A_2x)^d, \ldots, x_n + (A_nx)^d \right) \]
are linearly triangularizable if (1) \( \text{rk} A \leq 2 \) or (2) \( \text{cork} A \leq 2 \)
and \( d \geq 3 \) or (3) \( \text{cork} A = 3, d \geq 5 \) and the diagonal of \( A \) is nonzero.
Furthermore, we show that the triangularizations can be chosen power linear as well.

1 Introduction

The famous Jacobian Conjecture, which was first formulated by O.H. Keller in 1939, for short JC, asserts that for every \( n \geq 1 \) the following holds:

\[ \text{If } F = (F_1, F_2, \ldots, F_n) \text{ is a polynomial map over } \mathbb{C} \text{ with constant nontrivial Jacobian determinant, then } F \text{ is invertible.} \]

In the 1980’s, there are two famous reduction results. At first, it is shown that in order to prove the JC, it suffices to verify the JC for polynomial maps \( F \) over \( \mathbb{C} \) of special cubic homogeneous form:

\[ F = x + H = (x_1 + H_1, x_2 + H_2, \ldots, x_n + H_n) \]

where each component \( H_i \) of \( H \) is either zero or homogeneous of degree 3, see [1]. Later, Ludwik Drużkowski showed in [8] that in addition, one may assume that each component \( H_i \) of \( H \) is a third power of a linear form:

\[ F = x + (Ax)^3 = (x_1 + (A_1x)^3, x_2 + (A_2x)^3, \ldots, x_n + (A_nx)^3) \]

where \( x = (x_1, x_2, \ldots, x_n) \), \( A_i \) is the \( i \)-th row of an \( (n \times n) \)-matrix \( A \), and \( A_i x \)
is the matrix product 

\[
\begin{pmatrix}
A_{i1} & A_{i2} & \cdots & A_{in}
\end{pmatrix}
\begin{pmatrix}
x_1 \\
x_2 \\
\vdots \\
x_n
\end{pmatrix}
\]

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For the case \( \text{deg} F \leq 2 \), S. Wang had already proved in 1980 that the JC is true over any field of characteristic \( \neq 2 \), see [17] and [1].

In 1993, David Wright showed that in case \( n = 3 \), the JC holds for maps \( F \) having special cubic homogeneous form, see [18]. In particular \( F \) is so called ‘linearly triangularizable’, see definition 2.5. In 1994, the result of Wright was extended to the case \( n = 4 \) by Engelbert Hubbers, see [13], but for \( n = 4 \), maps of special cubic homogeneous form are not always linearly triangularizable. Hubbers used a (for those days) strong computer to get these results.

More than 10 years later, the result of Wright was extended in another direction: Arno van den Essen and the second author showed that in case \( n = 3 \) the JC holds for maps \( F \) having special homogeneous form in general (not just cubic) in [2]. The main theorem of [2] asserts that \( F \) is even linearly triangularizable, just as in the cubic case.

But let us focus on special cubic linear maps \( x + (Ax)^3 \) and, more generally, special power linear maps \( x + (Ax)^d \), from now on. At the same time that Wright showed the case \( n = 3 \) for special homogeneous cubic maps, Drużkowski showed that for special cubic linear maps \( F = x + (Ax)^3 \) with \( \text{rk} A \leq 2 \) or \( \text{cork} A \leq 2 \), \( F \) is invertible, see [9]. In particular, \( F \) is tame.

Although the results of Drużkowski for degree \( d = 3 \) generalize to degree \( d \geq 3 \) in a straightforward manner, we have chosen to rewrite these results. The main reason for this is that the proofs of Drużkowski are very sketchy; at some points, one can better speak of ‘guidelines of how to prove’.

Furthermore, Drużkowski only proved tameness in [9], which is weaker than linear triangularizability, but for the case \( \text{cork} A \leq 2 \), his proof is powerful enough for linear triangularizability, as Charles Ching-An Cheng observes in [4]. In the same article, Cheng proves linear triangularizability for the case \( \text{rk} A = 2 \) and \( d = 3 \).

But this proof is quite long. Cheng presents a much shorter proof for the case \( \text{rk} A = 2 \) and \( d \) arbitrary in [6], by showing the following result (Theorem 2 in [6]):

**Theorem 1.1.** Let \( F = x + (Ax)^d \) be a power linear Keller map, \( r = \text{rk} A \), and assume that all special homogeneous Keller maps of degree \( d \) in dimension \( r \) are linearly triangularizable. Then \( F \) is linearly triangularizable as well.

Since it is a classical result that for \( r = 2 \), the conditions of this theorem are fulfilled (see [1], [2] or [6]), the case \( \text{rk} A = 2 \) and \( d \) arbitrary follows. As mentioned above, the main result of [2] was exactly the case \( r = 3 \) of the conditions of the above theorem for all \( d \), so the case \( \text{rk} A = 3 \) and \( d \) arbitrary follows as well, as mentioned in [2].

We shall show that power linear Keller maps \( F = (x_1 + (A_1 x)^d, x_2 + (A_2 x)^d, \ldots, x_n + (A_n x)^d) \) are linearly triangularizable in each of the following cases:

1. \( \text{rk} A \leq 2 \),
2. \( \text{cork} A \leq 2 \) and \( d \geq 3 \),
3. \( \text{cork} A = 3 \), \( d \geq 5 \) and the diagonal of \( A \) is nonzero.
Furthermore, we show that in all of the above cases, the triangularizations can be chosen power linear as well. For a significant part, our results are based on the work of Družkowski in [9].

Although the results for \( \text{rk} A \leq 2 \) are valid for any \( d \), those for \( \text{cork} A \leq 2 \) apply only to the case \( d \geq 3 \). This restriction is not important for the JC, since it has already been proved for any polynomial map over \( \mathbb{C} \) with degree \( d \leq 2 \). On the other hand, the invertibility statement of the JC is weaker than linear triangularizability, so it is worth mentioning that in 2002, Cheng proved that quadratic linear Keller maps \( x + (Ax)^\ast 2 \) with \( \text{cork} A = 1 \) are linearly triangularizable, see [5].

In the last section, we present a quadratic linear map in dimension 6 with \( \text{rk} A = \text{cork} A = 3 \), which, as observed above, linearly triangularizable, but without a linear triangularization that is quadratic linear as well. So in our result for \( \text{cork} A = 3 \), the assumption \( d \geq 5 \) or at least some assumption on \( d \), is necessary.

2 Definitions and preliminaries

Definition 2.1. Write \( A^\ast \) for the transpose of a matrix \( A \). Now let \( A \) be an \((n \times n)\)-matrix. We write \( e_i \) for the \( i \)-th standard basis vector over \( \mathbb{C}^n \). Viewing vectors as column matrices, the matrix product \( Ae_i \) evaluates to the \( i \)-th column of \( A \) and \( e_i^\ast A \) evaluates to the \( i \)-th row of \( A \). But we will just write \( A_i \) for the \( i \)-th row of \( A \).

Definition 2.2. We call a map \( H \) power linear (of degree \( d \)) if \( H \) is of the form 
\[
H = (Ax)^\ast d := ((A_1x)^d, (A_2x)^d, \ldots, (A_nx)^d)
\]
and a map \( F \) special power linear (of degree \( d \)) if \( F \) is of the form 
\[
F = x + (Ax)^\ast d = (x_1 + (A_1x)^d, x_2 + (A_2x)^d, \ldots, x_n + (A_nx)^d)
\]
So \( H \) is power linear if and only if \( x + H \) is special power linear.

Definition 2.3. Let \( F \) be a polynomial map. We say that \( F \) is upper/lower triangular if its Jacobian \( \mathcal{J}F \) is upper/lower triangular. We call \( F \) triangular if it is either upper or lower triangular.

A triangular Keller map is tame and hence invertible.

Definition 2.4. Let \( F = x + H \) be a polynomial map. We call \( F \) special homogeneous (of degree \( d \)) if \( H \) is homogeneous (of degree \( d \)).

In [1, lemma 4.1], it is shown that a special homogeneous map of degree \( d \geq 2 \) is a Keller map, if and only if \( \mathcal{J}H \) is nilpotent.

Definition 2.5. Let \( F \) be a polynomial map over \( \mathbb{C} \). We call \( F \) linearly triangularizable if there exists a \( T \in \text{GL}_n(\mathbb{C}) \) such \( T^{-1} \circ F \circ T \) is triangular.
A linear triangularizable map can be triangularized to both an upper and a lower triangular map: take \( T = (x_n, x_{n-1}, \ldots, x_1) \) to get from lower to upper and vice versa.

**Proposition 2.6.** If \( F = x + H \) is a linearly triangularizable Keller map and the components of \( H \) do not have linear parts, then \( JH \) is nilpotent.

**Proof.** The proof is left as an exercise to the reader. A stronger result can be found in [10, Th. 1.6].

**Proposition 2.7.** If \( F = x + H \) is a triangular Keller map and the components of \( H \) do not have linear parts, then \( JH \) has only zeros on its diagonal.

**Proof.** From proposition 2.6, it follows that \( JH \) is nilpotent. Since a nilpotent matrix over a reduced ring has only eigenvalue zero and the diagonal of a triangular matrix is formed by its eigenvalues, it follows that \( JH \) has only zeros on its diagonal.

**Definition 2.8.** Let \( f \in \mathbb{C}[x] = \mathbb{C}[x_1, x_2, \ldots, x_n] \). We write \( \deg f \) for the total degree of \( f \). We write \( \deg_x f \) for the degree of \( f \), seen as a polynomial in \( x_i \) over \( \mathbb{C}[x_1, \ldots, x_{i-1}, x_{i+1}, \ldots, x_n] \). We write \( \deg_{x_i, x_j, x_k} f \) for the (total) degree of \( f \), seen as polynomial in \( x_i, x_j, x_k \).

### 3 Some results on linear dependence

**Lemma 3.1.** Let \( H := (Ax)^d \) such that \( JH \) is nilpotent. Assume that the first \( r \) rows of \( A_1, A_2, \ldots, A_r \) of \( A \) are independent and the last \( n - r \) rows of \( A \) are dependent of \( A_{r-1} \) and \( A_r \) only. Assume a similar condition on the columns of \( A \), i.e. the last \( n - r \) columns of \( A \) are dependent of \( Ae_{r-1} \) and \( Ae_r \) only. Then the components of \( H := (Ax)^d \) are linearly dependent.

**Proof.** Write \( Ae_{r+i} = \lambda_{r+i} Ae_{r-1} + \mu_{r+i} Ae_r \). Put

\[
L = \begin{pmatrix}
    x_1 \\
    \vdots \\
    x_{r-2} \\
    x_{r-1} - \lambda_{r+1} x_{r+1} - \cdots - \lambda_n x_n \\
    x_r - \mu_{r+1} x_{r+1} - \cdots - \mu_n x_n \\
    x_{r+1} \\
    \vdots \\
    x_n
\end{pmatrix}
\]

and let \( B := A \cdot JL \). Then the last \( n - r \) columns of \( B \) and hence those of \( JH \)
are zero, where
\[
\tilde{H} := L^{-1} \circ H \circ L = \begin{pmatrix}
(B_1x)^d \\
\vdots \\
(B_{r-2}x)^d \\
(B_{r-1}x)^d + \lambda_{r+1}(B_{r+1}x)^d + \cdots + \lambda_n(B_nx)^d \\
(B_rx)^d + \mu_{r+1}(B_{r+1}x)^d + \cdots + \mu_n(B_nx)^d \\
\vdots \\
(B_nx)^d
\end{pmatrix}
\]

Each row \(B_{r+i}\) with \(i \geq 1\) is a linear combination of \(B_{r-1}\) and \(B_r\), for a similar statement holds for the rows of \(A\). So \(\hat{H} := (\tilde{H}_1, \ldots, \tilde{H}_{r-2}, \tilde{H}_{r-1}, \tilde{H}_r)\) is of the form
\[
\hat{H} = \begin{pmatrix}
(B_1x)^d \\
\vdots \\
(B_{r-2}x)^d \\
p(B_{r-1}x, B_rx) \\
q(B_{r-1}x, B_rx)
\end{pmatrix}
\]

Furthermore, since the last \(n - r\) columns of \(\mathcal{J}\hat{H}\) are zero, the \((r \times r)\)-matrix \(\mathcal{J}\hat{H}\) is nilpotent as well. In particular, \(\det \mathcal{J}\hat{H} = 0\). If \(p(B_{r-1}x, B_rx)\) and \(q(B_{r-1}x, B_rx)\) are algebraically independent, then all linear forms \(B_ix\) with \(i \leq r\) are algebraically dependent of the components of \(\hat{H}\). So
\[
\text{trdeg}_C\hat{H} = \text{trdeg}_C(B_1x, \ldots, B_rx) = \text{trdeg}_C(A_1x, \ldots, A_rx) = r
\]

for the first \(r\) rows of \(A\) are linearly independent. This contradicts \(\det \mathcal{J}\hat{H} = 0\), so \(p(B_{r-1}x, B_rx)\) and \(q(B_{r-1}x, B_rx)\) are algebraically dependent. But with \(p\) and \(q\) homogeneous of the same degree \(d\), this dependence relation refines to a linear relation, say that \(\nu_1p + \nu_2q = 0\) with \(\nu \neq 0\). Then
\[
\nu_1((B_{r-1}x)^d + \lambda_{r+1}(B_{r+1}x)^d + \cdots + \lambda_n(B_nx)^d) + \\
\nu_2((B_rx)^d + \mu_{r+1}(B_{r+1}x)^d + \cdots + \mu_n(B_nx)^d) = 0
\]

So the components of \((Bx)^*d\), and hence those of \(H := (Ax)^*d\) also, are linearly dependent.

The preceding lemma is a special case of the following theorem:

**Theorem 3.2.** Let \(H := (Ax)^*d\) such that \(\mathcal{J}H\) is nilpotent. Assume that the first \(r\) rows of \(A_1, A_2, \ldots, A_r\) of \(A\) are independent and the last \(n - r\) rows of \(A\) are dependent of \(A_{r-1}\) and \(A_r\) only. Then the components of \(H := (Ax)^*d\) are linearly dependent.

**Proof.** Since the rows of \(A\) are dependent, the columns are dependent as well. We distinguish two cases:
• There is an \( i \leq r - 2 \) such that column \( Ae_i \) of \( A \) is dependent of the other columns of \( A \).

Then there is a vector \( \lambda \) with \( \lambda_i \neq 0 \) for some \( i \leq r - 2 \) such that \( A\lambda = 0 \). Replacing \( H \) by \( P^{-1} \circ H \circ P \) for a suitable permutation \( P \) within \( x_1, x_2, \ldots, x_{r-2} \), we may assume that \( \lambda_i \neq 0 \). Since

\[
JH = d \begin{pmatrix}
A_{11}(A_1x)^{d-1} & A_{12}(A_1x)^{d-1} & \cdots & A_{1n}(A_1x)^{d-1} \\
A_{21}(A_2x)^{d-1} & A_{22}(A_2x)^{d-1} & \cdots & A_{2n}(A_2x)^{d-1} \\
\vdots & \vdots & \ddots & \vdots \\
A_{n1}(A_nx)^{d-1} & A_{n2}(A_nx)^{d-1} & \cdots & A_{nn}(A_nx)^{d-1}
\end{pmatrix}
\]

(1)

the expression \( \det(TI_n + JH) \), which is \( T^n \) on account of the nilpotence of \( JH \), can be seen as a polynomial in the transcendent ‘variables’ \( A_1x, A_2x, \ldots, A_rx \). Since \( r - 2 \geq 1 \), ‘variable’ \( A_1x \) only appears in the first row of (1). So substituting \( A_1x = 0 \) in \( JH \) just makes the first row of \( JH \) zero. This substitution does not affect the condition \( \det(TI_n + JH) = T^n \).

So \( JH \) is nilpotent, where \( \tilde{H} := (0, H_2, \ldots, H_n) \). Next, let

\[
\tilde{H} := L^{-1} \circ \tilde{H} \circ L = \hat{H} \circ L
\]

where \( L = x + \lambda_1^{-1}(0, \lambda_2x_1, \ldots, \lambda_nx_1) \). Now \( x + \hat{H} \) is power linear of degree \( d \) as well, but both the first row and the first column of \( JH \) are zero. Hence \( x + \hat{H} \) is essentially a power linear map in dimension \( n - 1 \), and the result follows by induction.

• For each \( i \leq r - 2 \), column \( Ae_i \) of \( A \) is independent of the other columns of \( A \).

Since in particular the first \( r - 2 \) columns of \( A \) are independent, there exists a basis of the column space of \( A \) of the form \( Ae_1, Ae_2, \ldots, Ae_{r-2}, Ae_{i_1}, Ae_{i_2} \). Furthermore, for each \( j \geq r - 1 \), column \( Ae_j \) is a linear combination of \( Ae_{i_1} \) and \( Ae_{i_2} \) only. We shall show that we may assume that \( i_1 = r - 1 \) and \( i_2 = r \), in order to be able to apply lemma 3.1.

For that purpose let us look at the rows \( A_{i_1} \) and \( A_{i_2} \) of \( A \). If both rows are dependent, then \( H_{i_1} \) and \( H_{i_2} \) are linearly dependent and we are done. So assume that \( A_{i_1} \) and \( A_{i_2} \) are independent. Since the last \( n - r \) rows of \( A \) are linear combinations of \( A_{r-1} \) and \( A_r \) and \( i_1, i_2 \geq r - 1 \), both \( A_{i_1} \) and \( A_{i_2} \) are linear combinations of \( A_{r-1} \) and \( A_r \). Hence the spaces \( CA_{i_1} + CA_{i_2} \) and \( CA_{r-1} + CA_r \) are equal.

Hence \( A_{i_1} \) and \( A_{i_2} \) can take the role of \( A_{r-1} \) and \( A_r \), i.e. the rows \( A_1, A_2, \ldots, A_{r-2}, A_{i_1}, A_{i_2} \) are independent and each row \( A_j \) with \( j \geq r - 1 \) is a linear combination of \( A_{i_1} \) and \( A_{i_2} \) only.

Replacing \( H \) by \( P^{-1} \circ H \circ P \) for a suitable permutation \( P \) within \( x_{r-1}, x_r, \ldots, x_n \), we may assume that \( H \) satisfies the conditions of lemma 3.1. So the components of \( H \) are linearly dependent. \( \Box \)
The proof of theorem 3.2 and its preceding lemma was essentially given by Druzkowski in [9], where he proved the case \( r = n - 2 \) of theorem 3.2. The remaining theorems in this section show that under certain conditions, the components of \( H \) are not only linearly dependent, but the linear dependence even restricts to two components of \( H \), i.e. \( H_i = sH_j \) for some \( i \neq j \) and an \( s \in \mathbb{C} \).

**Lemma 3.3.** Let \( L_1, L_2, \ldots, L_r \in \mathbb{C}[x] \) be linear such that \( 2 \leq r \leq d + 1 \) and

\[
\lambda_1 L_1^d + \lambda_2 L_2^d + \ldots + \lambda_r L_r^d = 0
\]  

for some \( \lambda = (\lambda_1, \ldots, \lambda_r) \neq 0. \) Then there are \( i \neq j \) and an \( s \in \mathbb{C} \) such that \( L_i = sL_j. \)

**Proof.** Assume the opposite. In particular, \( L_1 \neq sL_r \) and \( L_r \neq sL_1 \) for all \( s \in \mathbb{C} \), whence \( L_1 \) and \( L_r \) are independent. There exists a linear basis \( y_1, y_2, \ldots, y_n \) of \( \mathbb{C}[x] \) with \( y_1 = L_1 \) and \( y_2 = L_r. \)

The case \( d = 1 \) is easy, so assume \( d \geq 2. \) Differentiating (2) with respect to \( y_1 \) gives

\[
\mu_1 L_1^{d-1} + \mu_2 L_2^{d-1} + \ldots + \mu_{r-1} L_{r-1}^{d-1} = 0
\]

for certain \( \mu_i \in \mathbb{C} \). In particular, \( \mu_1 = d\lambda_1 \), whence not all \( \mu_i \) are zero. Hence, the result follows by induction on \( d \).

The following theorem generalizes Theorem 3.1 of [16] (the case \( \text{cork}A = 3 \) of this theorem). [16] is a co-production of Song Shuang and the first author.

**Theorem 3.4.** Assume \( H \) is of the form \((Ax)^d\) such that \( \text{cork}A \leq d - 2, \) \( \text{tr}JH = 0, \) and the diagonal of \( A \) is nonzero. Then there are \( i \neq j \) and an \( s \in \mathbb{C} \) such that \( A_i = sA_j \neq 0. \)

**Proof.** Since the diagonal of \( JH \) is nonzero, we can replace \( H \) by \( P^{-1} \circ H \circ P \) to get \( A_{11} \neq 0, \) where \( P \) is a permutation. Similarly, we can make the first \( r \) rows of \( A \) independent in addition, where \( r = \text{rk}A \geq n - (d - 2). \) Since \( \text{tr}JH = 0, \) we have

\[
dA_{11}(A_1 x)^{d-1} + dA_{22}(A_2 x)^{d-1} + \cdots + dA_{nn}(A_n x)^{d-1} = 0
\]  

(3)

Since the first \( r \) rows of \( A \) are independent, there exists a basis \( y \) of \( \mathbb{C}x_1 + \mathbb{C}x_2 + \cdots + \mathbb{C}x_n \) such that \( A_i x = y_i \) for all \( i \leq r. \) Differentiating (3) with respect to \( y_1 \) gives

\[
d(d-1)A_{11}(A_1 x)^{d-2} + \lambda_{r+1}(A_{r+1} x)^{d-2} + \cdots + \lambda_n(A_n x)^{d-2} = 0
\]

for certain \( \lambda_i \in \mathbb{C}. \) These are \( n - r + 1 \leq d - 1 \) linear powers (powers of linear forms). Now apply lemma 3.3 to get \( A_i = sA_j \) for some \( i \neq j \) and \( s \in \mathbb{C} \) with \( i, j \in \{1, r+1, r+2, \ldots, n\}. \)

**Theorem 3.5.** Assume \( H \) is as in theorem 3.2 and \( \text{cork}A \leq d - 1. \) Then there are \( i \neq j \) and an \( s \in \mathbb{C} \) such that \( A_i = sA_j. \)
From theorem 3.2, it follows that there is a linear relation between the components of $H$. Similar to the proof of theorem 3.4 (but with $d$ instead of $d-1$), one can show that this relation is of the form $H_i = \alpha H_j$ for some $i \neq j$. So $A_i = sA_j$ for some $s \in \mathbb{C}$.

We will use the above theorems in the next section.

### 4 Linear triangularization to power linear maps

The following lemma is crucial in both [9] and our study of power linear maps $(Ax)^{d}$ where $A$ has a small corank. It can be found at the beginning of page 238 in [9].

**Lemma 4.1.** Let $H = (Ax)^{d}$ such that $JH$ is nilpotent. If $A$ has a principal minor of any size which determinant is nonzero, then there exists a relation $R \neq 0$ such that

$$R((A_1x)^{d-1}, (A_2x)^{d-1}, \ldots, (A_nx)^{d-1}) = 0$$

and $\deg_y R(y) \leq 1$ for all $i \leq n$. Furthermore, if $A_k = 0$ for some $k$, then $\deg_y R = 0$ as well.

**Proof.** Write

$$\det(TI_n + d \begin{pmatrix} A_{11}y_1 & A_{12}y_1 & \cdots & A_{1n}y_1 \\ A_{21}y_2 & A_{22}y_2 & \cdots & A_{2n}y_2 \\ \vdots & \vdots & \ddots & \vdots \\ A_{n1}y_n & A_{n2}y_n & \cdots & A_{nn}y_n \end{pmatrix})$$

$$= T^n + R_1(y)T^{n-1} + R_2(y)T^{n-2} + \cdots + R_{n-2}(y)T^2 + R_{n-1}(y)T + R_n(y)$$

Since $JH$ is nilpotent, $\det(TI_n + JH) = T^n$. It follows from (1) that the coefficient of $T^{n-j}$ of $\det(TI_n + JH)$ equals

$$R_j((A_1x)^{d-1}, (A_2x)^{d-1}, \ldots, (A_nx)^{d-1}) = 0$$

for all $j \geq 1$. Furthermore, it follows from the definition of determinant that $\deg_{y_i} R_j \leq 1$ for all $i, j$. For some $j$, $A$ has a principal minor of size $j$ which determinant is $\alpha \neq 0$, say with rows and columns $i_1, i_2, \ldots, i_j$. Then the coefficient of $y_{i_1}y_{i_2} \cdots y_{i_j}$ of $R_j$ equals $d\alpha$, whence $R_j \neq 0$.

If $A_k = 0$, then all minors with row $k$ of $A$ have determinant zero, whence $\deg_{y_k} R_j = 0$.

In all remaining lemmas in this section, relations $R$ between linear powers $L_i^a, L_j^d, \ldots, L_m^d$ with $\deg_y R \leq 1$ for all $i \leq m$ are studied. For such relations, conditions are formulated that imply $L_i = sL_j$ for some $i \neq j$ and an $s \in \mathbb{C}$. 

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Lemma 4.2. Let $d \geq 2$ and $R$ be a nonzero relation with $\deg_{y_i} R \leq 1$ such that

$$R(x_1^d, x_2^d, \ldots, x_r^d, (\lambda_1 x_1 + \lambda_2 x_1 + \cdots + \lambda_r x_r)^d) = 0$$

Then $\lambda = \lambda_i e_i$ for some $i$.

Proof. Since $x_1^d, x_2^d, \ldots, x_r^d$ are algebraically independent, it follows that $R$ has a term of the form

$$\alpha \cdot y_1^{t_1} \cdots y_r^{t_r} \cdot y_{r+1}$$

with $\alpha \neq 0$ and $0 \leq t_i \leq 1$ for all $i$. The coefficient of $x_1^{d_1} x_2^{d_2} \cdots x_r^{d_r} x_j^{d_j-1} x_k$ in (4) equals $(d-1)\alpha \lambda_j \lambda_k = 0$, so $\lambda_j \lambda_k = 0$ for all $j \neq k$. It follows that $\lambda$ has at most one nonzero coordinate, i.e. $\lambda = \lambda_i e_i$ for some $i$.

Lemma 4.3. Let $d \geq 2$ and $R$ be a nonzero relation with $\deg_{y_i} R \leq 1$ such that

$$R(x_1^d, x_2^d, \ldots, x_r^d, (\lambda_1 x_1 + \lambda_2 x_2 + \cdots + \lambda_r x_r)^d, (\mu_1 x_1 + \mu_2 x_2 + \cdots + \mu_r x_r)^d) = 0$$

Assume further that $\lambda_i = \mu_i = 0$ for at most $r-3$ $i$'s. Then either $\lambda = \lambda_i e_i$ for some $i$ or $\mu = \mu_i e_i$ for some $i$ or $\lambda$ and $\mu$ are dependent.

Proof. Assume that $\lambda$ and $\mu$ are independent. Without loss of generality, we assume that $(\lambda_1, \lambda_2)$ and $(\mu_1, \mu_2)$ are independent. The cases $\deg_{y_{r+1}} R = 0$ and $\deg_{y_{r+2}} R = 0$ follow from lemma 4.2. So assume the opposite.

i) Suppose first that $\lambda_1 = \mu_2 = 0$. Then $\lambda_2 \mu_1 \neq 0$. Since $\deg_{y_{r+2}} R = 1$, $R$ has a term of the form

$$\alpha y_1^{t_1} y_2^{t_2} \cdots y_r^{t_r} \cdot y_{r+1}^{t_{r+1}} y_{r+2}$$

with $0 \leq t_i \leq 1$ for all $i$. If $t_{r+1} = 0$, then by looking at the term

$$x_1^{d_1} x_2^{d_2} \cdots x_r^{d_r} \cdot (x_1^{d-1} x_m)$$

of (5), we see that $\mu_m = 0$ for all $m \neq 1$, i.e. $\mu = \mu_1 e_1$. So assume $t_{r+1} = 1$. Looking at the term

$$x_1^{d_1} x_2^{d_2} \cdots x_r^{d_r} \cdot x_2^{d-1} x_1^{d-1}$$

of (5), we see that $\lambda_l \mu_l = 0$ for all $l \geq 3$. Assume $\lambda = \lambda_2 e_2$. Then there is an $l \geq 3$ such that $\lambda_l \neq 0$. So $\mu_l = 0$. Looking at the term

$$x_1^{d_1} x_2^{d_2} \cdots x_r^{d_r} \cdot x_2^{d-1} x_1 x_m x_1^{d-1}$$

gives $\mu_m = 0$ for all $m \geq 3$. So $\mu = \mu_1 e_1$.

So assume $(\lambda_i, \mu_{3-i}) \neq 0$ for $i = 1, 2$. Since $(\lambda_1, \lambda_2)$ and $(\mu_1, \mu_2)$ are independent, at least three of their four coordinates are nonzero. Assume without loss of generality that $\lambda_1 \lambda_2 \mu_1 \neq 0$. If $\mu_2 = 0$, then we may assume that $\mu_3 \neq 0$ on account of the assumption $\mu \neq \mu_1 e_1$. 


If $\mu_2 \neq 0$, then $\lambda_1 \lambda_2 \mu_1 \mu_2 \neq 0$. From the assumption $\lambda_i = \mu_i = 0$ for at most $r-3$ $i$'s, it follows that $\lambda_i \neq 0$ or $\mu_i \neq 0$ for some $i \geq 3$. So without loss of generality, we may assume $\mu_3 \neq 0$. So assume $\mu_3 \neq 0$ regardless of whether $\mu_2 = 0$ or not.

Assume that $(\lambda_2, \lambda_3)$ and $(\mu_2, \mu_3)$ are dependent. Then $\mu_2 \mid \lambda_2 \mu_3 \neq 0$, so $\lambda_2 \mu_2 \neq 0$. If we interchange $(\lambda_1, \mu_1)$ and $(\lambda_2, \mu_2)$, which can be realized by flipping $x_1$ and $x_2$, $(\lambda_2, \lambda_3)$ and $(\mu_2, \mu_3)$ get independent but the condition $\lambda_1 \mu_1 \neq 1$ is not affected. So we may assume that $(\lambda_2, \lambda_3)$ and $(\mu_2, \mu_3)$ are independent and in addition $\lambda_1 \mu_1 \neq 0$.

ii) We show that the above assumptions lead to a contradiction. Replacing $R$ by $R(y_1, y_2, \ldots, y_r, \lambda_2^2 y_{r+1}, \mu_2^2 y_{r+2})$, we may assume that $\lambda_1 = \mu_1 = 1$.

Write $\lambda_1 x_1 + \lambda_2 x_2 + \cdots + \lambda_r x_r = x_1 + L$ and similarly $\mu_1 x_1 + \mu_2 x_2 + \cdots + \mu_r x_r = x_1 + M$.

Let $s := \deg_{y_1, y_{r+1}, y_{r+2}} R$. Notice that $\deg_{y_i} R \leq 1$ for all $i$. If $s \geq 3$, then $s = 3$ and the left hand side of (5) has degree $3d$ with respect to $x_1$; contradiction. Since $\deg_{y_{r+1}} R \neq 0$, $s \geq 1$. So two cases remain:

- $s = 1$:

  We can write
  
  $$R = R_1 y_1 + R_2 y_{r+1} + R_3 y_{r+2} + R_4$$

  with $R_i \in \mathbb{C}[y_2, \ldots, y_r]$. Looking at the coefficient of $x_1^{d-1}$ in (5) gives
  
  $$R_1 x_1^{d-1} + R_2 x_2^{d-1} + \cdots + R_r x_r^{d-1} L = -R_3(x_2^d, \ldots, x_r^d) M$$

  Assume $R_2 \neq 0$. Notice that $d \geq 2$. Reduction modulo $x_i^d - y_i$ for all $i$ gives $R_2 L = -R_3 M$. Next, a generic substitution into the $y_i$’s gives $L = \alpha M$ for some $\alpha \in \mathbb{C}$. So $L$ and $M$ are linearly dependent. This contradicts the independence of $(\lambda_2, \lambda_3)$ and $(\mu_2, \mu_3)$, so $R_2 = R_3 = 0$. Looking at the coefficient of $x_1^d$ in (5) gives $R_1 = 0$. So $R = R_4$.

  This contradicts $s = 1$.

- $s = 2$:

  We can write
  
  $$R = R_1 y_{r+1} y_{r+2} + R_2 y_1 y_{r+2} + R_3 y_1 y_{r+1} + R_4$$

  with $R_i \in \mathbb{C}[y_2, \ldots, y_r]$ for all $i \leq 3$ and $\deg_{y_1, y_{r+1}, y_{r+2}} R_4 \leq 1$.

  Looking at the coefficient of $x_1^{2d-1}$ in (5) gives
  
  $$(R_1 + R_3)(x_2^d, \ldots, x_r^d) L = -(R_1 + R_2)(x_2^d, \ldots, x_r^d) M$$

  and $(R_1 + R_3) = (R_1 + R_2) = 0$ follows similar as $R_2 = R_3 = 0$ in the case $s = 1$. Looking at the coefficient of $x_1^{2d}$ in (5) gives $R_1 + R_2 + R_3 = 0$, so $R_2 = R_3 = 0$ and also $R_1 = 0$. So $R = R_4$.

  This contradicts $s = 2$. 

$\square$
Theorem 4.4. Assume $A$ is a matrix of corank 2 at most, $d \geq 3$ and $H = (Ax)^d$ such that $JH$ is nilpotent. Then there exists a $T \in \text{GL}_n(\mathbb{C})$ and a lower triangular matrix $B$ such that
\[
T^{-1} \circ (Ax)^d \circ T = (Bx)^d
\]

Proof. Assume first that every principal minor of $A$ has determinant zero. From [9, lemma 1.2] (see also [12, prop. 6.3.9]), it follows that there is a permutation $P$ such that $P^{-1}AP$ is lower triangular. So take $T = P$.

Assume next that $A$ has an invertible principal minor. From lemma 4.1, it follows that there exists a nonzero relation $R$ such that
\[
R((A_1x)^{d-1}, (A_2x)^{d-1}, \ldots, (A_nx)^{d-1}) = 0
\]

Let $r := \text{rk}A \geq n - 2$. After a suitable permutation, we have that the rows $A_1, A_2, \ldots, A_r$ are independent,
\[
A_{r+1} = \lambda_1A_1 + \lambda_2A_2 + \cdots + \lambda_rA_r
\]
and, in case $r = n - 2$,
\[
A_{r+2} = \mu_1A_1 + \lambda_2A_2 + \cdots + \mu_rA_r
\]

We first show that $A_i = sA_j$ for some $i \neq j$ and $s \in \mathbb{C}$. The case $r = n - 1$ follows from lemma 4.2, so assume that $r = n - 2$. The case $\lambda_i = \mu_i = 0$ for at most $r - 3$ i’s follows from lemma 4.3, so assume $\lambda_i = \mu_i = 0$ for at least $r - 2$ i’s. Replacing $A$ by $P^{-1}AP$ for a suitable permutation $P$, we get that $\lambda_i = \mu_i = 0$ for all $i \leq r - 2$, and theorem 3.5 applies. So $A_i = sA_j$ for some $i \neq j$ and $s \in \mathbb{C}$.

So the components of $H$ are linearly dependent. Replacing $H$ by $T^{-1} \circ H \circ T$ for a suitable linear transformation $T$, we get $H_1 = 0$ and hence $A_1 = 0$.

This transformation may make all principal minor determinants zero, but then, again by [9, lemma 1.2], there is a permutation matrix $P$ such that $P^{-1}AP$ is lower triangular. So we may assume that there is still a nonzero principal minor determinant in $A$. From lemma 4.1 it follows that there exists a nonzero relation $R_1$ such that
\[
R_1((A_2x)^{d-1}, \ldots, (A_nx)^{d-1}) = 0
\]

After a suitable permutation, we have that the rows $A_2, A_3, \ldots, A_{r+1}$ are independent and
\[
A_{r+2} = \lambda_2A_2 + \lambda_3A_3 + \cdots + \lambda_{r+1}A_{r+1}
\]

Applying lemma 4.2 again gives $A_i = sA_j$ for some $i \neq j$ with $i, j \neq 1$ and $s \in \mathbb{C}$, i.e. a linear relation between $(A_2x)^d, \ldots, (A_nx)^d$. So after a suitable linear transformation, we have $A_2 = 0$ as well.

Since $\text{cork}A \leq 2$, $(A_3x)^{d-1}, \ldots, (A_nx)^{d-1}$ are algebraically independent. It follows from lemma 4.1 that all principal minor determinants of $A$ are zero. So again we can take for $T$ a suitable permutation matrix $P$. \qed
The proof of the above theorem was essentially given by Drużkowski in [9]. Drużkowski observed something more or less similar to lemma 4.3, but found it unnecessary to prove that in full detail.

**Lemma 4.5.** Let $d \geq 3$ and $R$ be a nonzero relation with $\deg_y R \leq 1$ such that

$$R(x_1^d, x_2^d, \ldots, x_r^d, (\lambda_1 x_1 + \lambda_2 x_1 + \cdots + \lambda_r x_r)^d, (\mu_1 x_1 + \mu_2 x_1 + \cdots + \mu_r x_r)^d) = 0 \quad (6)$$

Then either $\lambda = \lambda_i e_i$ for some $i$ or $\mu = \mu_i e_i$ for some $i$ or $\lambda$ and $\mu$ are dependent.

**Proof.** The cases $\deg_{y_i} R = 0$ and $\deg_{y_{r+2}} R = 0$ follow from lemma 4.2, so assume the opposite. The case $\lambda_i = \mu_i = 0$ for at most $r - 3$ $i$'s follows from lemma 4.3, so assume without loss of generality that $\lambda_i = \mu_i = 0$ for all $i \geq 3$.

Similar as in the proof of lemma 4.3, we assume that $\lambda_1 = \mu_1 = 1$ and write $\lambda_1 x_1 + \lambda_2 x_2 + \cdots + \lambda_r x_r = x_1 + L$ and $\mu_1 x_1 + \mu_2 x_2 + \cdots + \mu_r x_r = x_1 + M$.

Put $s := \deg_{y_1, y_r+1, y_{r+2}} R$. If $s \geq 3$, then $s = 3$ and the left hand side of (6) has degree $3d$ in $x_1$; contradiction. Since $\deg_{y_1} R \neq 0$, $s \geq 1$. So two cases remain:

- **$s = 1$:**
  
  Since $\lambda_i = \mu_i = 0$ for all $i \geq 3$, $R$ is in fact a relation between $x_1^d$, $x_2^d$, $(x_1 + L)^d$ and $(x_1 + M)^d$, say
  
  $$R_0(x_1^d, x_2^d, (x_1 + L)^d, (x_1 + M)^d) = 0$$
  
  for some homogeneous $R_0 \neq 0$ with $\deg_{y_1, y_3, y_4} R_0 \leq s$ and $\deg_{y_2} R_0 \leq 1$.

  If $R_0$ is linear, then it follows from lemma 3.3 and $d \geq 3$ that $L = 0$, $M = 0$ or $L = M$. If $R_0$ is not linear, then it follows from $s = 1$ that $R_0$ is quadratic and $y_2 \mid R_0$, for $R_0$ is homogeneous. Hence, $R_0$ decomposes into linear factors and can be chosen linear instead.

- **$s = 2$:**
  
  Write
  
  $$R = R_1 y_{r+1} y_{r+2} + R_2 y_1 y_{r+2} + R_3 y_1 y_{r+1} + R_4$$
  
  with $R_i \in \mathbb{C}[y_2, \ldots, y_t]$ for all $i \leq 3$ and $\deg_{y_1, y_{r+1}, y_{r+2}} R_4 \leq 1$. Looking at the coefficient of $x_1^{2d-1}$ in (6) gives
  
  $$(R_1 + R_4)(x_2^d, \ldots, y_r^d)L = -(R_1 + R_2)(x_2^d, \ldots, y_r^d)M$$
  
  Looking at the coefficient of $x_1^{2d}$ in (6), gives $R_1 + R_2 + R_3 = 0$, which implies $-R_2 L = R_3 M$.

  At last, the coefficient of $x_1^{2d-2}$ in (6) implies that the following is zero:
  
  $$2dR_1 LM + (d - 1)(R_1 + R_3)L^2 + (d - 1)(R_1 + R_2)M^2$$
  
  $$= 2dR_1 LM - (d - 1)R_2 L^2 - (d - 1)R_3 M^2$$
  
  $$= 2dR_1 LM + (d - 1)R_3 LM + (d - 1)R_2 LM$$
  
  $$= (d + 1)R_1 LM$$

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So $LM = 0$ or $R_1 = 0$. So assume $R_1 = 0$. Then $R_2 - R_3 = 0$. From $-R_2 = R_3$ and $-R_2L = R_3M$, it follows that either $R = R_4$, which contradicts $s = 2$, or $L = M$. \hfill \square

**Theorem 4.6.** If $H$ is as in theorem 3.4 and $corkA = 3$, then there exists a $T \in \text{GL}_n(\mathbb{C})$ and a lower triangular matrix $B$ such that

$$T^{-1} \circ (Ax)^{sd} \circ T = (Bx)^{sd}$$

**Proof.** Since the proof of theorem 4.6 is more or less similar to that of theorem 4.4, we only give a sketch of it.

From theorem 3.4 or [16, Th. 3.1], it follows that $A_i = sA_j$ for some $i \neq j$ and $s \in \mathbb{C}$, i.e. the components of $H$ are linearly dependent. So we may assume that the first row of $A$ is zero. Assume $A$ has a nonzero principal minor determinant. The conditions of theorem 3.4 imply that $3 = corkA \leq d - 2$, so $d \geq 5$. So it follows from lemmas 4.1 and 4.5 that we may assume that the first two rows of $A$ are zero. Next, it follows from lemmas 4.1 and 4.2 that we may assume that the first three rows of $A$ are zero. Since $corkA = 3$, all principal minors of $A$ have determinant zero. So $B$ as above exists. \hfill \square

Observe that in the proofs of theorems 4.4 and 4.6, the process of triangularization is as follows: first, all occurrences of $A_i = sA_j$ with $i \neq j$ and $s \in \mathbb{C}$ are eliminated by linear transformations ‘within $\mathbb{C}[x_i, x_j]$’. After that, $A$ is made triangular by a permutation transformation. This result does not follow from the methods of Drużkowski.

The above observation does not hold for power linear maps $(Ax)^{sd}$ with $rkA = 2$, but still there exist a triangularization of $(Ax)^{sd}$ that is power linear as well. The following theorem, which is in fact a closer look on what happens in the proof of Theorem 1 of [6], shows this result not only for $d \geq 3$, but for any $d \geq 1$.

**Theorem 4.7.** Assume $A$ is a matrix of rank $2$ at most and $J(Ax)^{sd}$ is nilpotent. Then there exists a $T \in \text{GL}_n(\mathbb{C})$ and a lower triangular matrix $B$ such that

$$T^{-1} \circ (Ax)^{sd} \circ T = (Bx)^{sd}$$

**Proof.** The case $rkA = 1$ was already done by Drużkowski in [9]. So assume that $rkA = 2$. Then there are two rows $A_{i_1}$ and $A_{i_2}$ of $A$ such that all other rows of $A$ are linear combinations of $A_{i_1}$ and $A_{i_2}$. There are $n - 2$ distinct unit vectors $e_{k_3}, \ldots, e_{k_n}$ such that the rows $A_{i_1}, A_{i_2}, e_{k_3}^t, \ldots, e_{k_n}^t$ are independent. Replacing $A$ by $P^{-1}AP$ for a suitable permutation $P$ makes that the rows $A_{i_1}, A_{i_2}, e_{k_3}^t, \ldots, e_{k_n}^t$ are independent.

Hence the matrix with those $n$ rows is invertible. So set

$$T := \begin{pmatrix} A_{i_1} & A_{i_2} \\ e_{k_3}^t & \ldots \\ \cdots & \cdots \\ e_{k_n}^t \end{pmatrix}^{-1}$$

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Then the last \( n - 2 \) rows of \( T \) are \( e_3^t, \ldots, e_n^t \) as well. Put \( \tilde{H} = T^{-1} \circ H \circ T \), where \( H = (Ax)^d \). The components \( \tilde{H}_3, \ldots, \tilde{H}_n \) of \( \tilde{H} \) are clearly linear powers. Write \( A_i = \lambda_i A_{j_1} + \mu_i A_{j_2} \) for all \( i \). Then

\[
A = \begin{pmatrix}
\lambda_1 & \mu_1 & 0 & \cdots & 0 \\
\lambda_2 & \mu_2 & 0 & \cdots & 0 \\
\vdots & \vdots & \ddots & \vdots & \vdots \\
\lambda_n & \mu_n & 0 & \cdots & 0
\end{pmatrix} \cdot T^{-1}
\]

So the last \( n - 2 \) columns of \( A \cdot T \) are zero. It follows that \( \tilde{H}_i \in \mathbb{C}[x_1, x_2] \) for each \( i \). Hence \( (x_1, x_2) + (\tilde{H}_1, \tilde{H}_2) \) is a homogeneous Keller map in dimension 2. Such maps are classified in e.g. [1]: we have either \( \tilde{H}_1 = \tilde{H}_2 = 0 \), in which case \( \tilde{H} \) is already of the form \( (Bx)^d \) with \( B \) triangular, or

\[
\begin{pmatrix}
\tilde{H}_1 \\
\tilde{H}_2
\end{pmatrix} = S^{-1} \circ \begin{pmatrix}
0 \\
x_1^d
\end{pmatrix} \circ S
\]

Now \( (S, x_3, \ldots, x_n)^{-1} \circ \tilde{H} \circ (S, x_3, \ldots, x_n) \) is of the form \( (Bx)^d \) with \( B \) triangular.

In case \( \text{rk} A = 1 \), Družkowski found a matrix \( B \) with \( n - 1 \) zero rows, but an argument similar as above would give a matrix \( B \) with \( n - 1 \) zero columns.

### 5 Some final remarks

At first, we like to mention that in [5], Cheng proves that in case \( \text{cork} A = 1 \), \( A_i = s A_j \) for some \( i \neq j \) and \( s \in \mathbb{C} \), also in the quadratic case. So the conclusion of theorem 4.4 holds for this case as well: see the proof of theorem 4.4. The following quadratic linear map \( (Ax)^2 \) in dimension 6 with \( \text{rk} A = \text{cork} A = 3 \), which is, as observed in the introduction, linearly triangularizable, but without a linear triangularization that is quadratic linear as well:

\[
H = \begin{pmatrix}
0 \\
0 \\
(x_1 + x_2 + x_3 - x_4 - x_5 + x_6)^2 \\
(x_1 - x_2 + x_3 - x_4 - x_5 + x_6)^2 \\
(x_1 - x_2 - x_3 + x_4 + x_5 - x_6)^2 \\
(x_1 + x_2 - x_3 + x_4 + x_5 - x_6)^2
\end{pmatrix}
\]

In order to prove that the above quadratic linear \( H \) has no ditto linear triangularization, we need the following normalization principle for triangular power linear maps.

**Proposition 5.1.** Let \( H = (Ax)^d \) be lower triangular. Then there exists an \( r \) and a \( G = (Bx)^d \) which is lower triangular as well, such that \( G_1 = G_2 = \cdots = G_r = 0 \) and \( G_{r+1}, G_{r+2}, \ldots, G_n \) are linearly independent over \( \mathbb{C} \).
Proof. Assume
\[ \lambda_1 H_1 + \lambda_2 H_2 + \cdots + \lambda_s H_s \]
is a linear dependence relation between the components of \( H \) with \( \lambda_s \neq 0 \). After a suitable linear transformation that does not affect the fact that \( H \) is lower triangular, we have \( H_s = 0 \). Repeating this argument, we get that all linear relations between the components of \( H \) are determined by zero components of \( H \).

Next, if \( H_s = 0 \), but \( H_i = 0 \) does not hold for all \( i \leq s \), then the map \( P^{-1} \circ H \circ P \) with \( P = (x_2, \ldots, x_s, x_1, x_{s+1}, \ldots, x_n) \), which is lower triangular as well, has more zero components at the beginning than \( H \) has, and the result follows by induction.

Now let \( E = (x_1, x_2, x_3 + x_4 + x_5 - x_6, x_4, x_5, x_6) \), then
\[
G := E^{-1} \circ H \circ E = \begin{pmatrix} 0 & 0 & 8x_1x_2 & (x_1 - x_2 + x_3)^2 & (x_1 - x_2 - x_3)^2 & (x_1 + x_2 - x_3)^2 \end{pmatrix}
\]
is a triangularization of \( H \). In order to prove that \( H \) has no triangularization that is quadratic linear as well, we show that \( \tilde{G} = T^{-1} \circ G \circ T \) cannot be both lower triangular just as \( G \) and quadratic linear just as \( H \).

Assume \( \lambda^t G = 0 \). Looking at \( (\frac{\partial}{\partial x_1})^2 G_i \) for all \( i \), we see that \( \lambda_4 + \lambda_5 + \lambda_6 = 0 \). Looking at \( (\frac{\partial}{\partial x_2})^2 G_i \) and \( (\frac{\partial}{\partial x_3})^2 G_i \) for all \( i \) as well, we see that \( \lambda_4 = \lambda_5 = \lambda_6 = 0 \). Since \( G_1 = G_2 = 0 \), \( \lambda_3 = 0 \) and the last four components of \( G \) are linearly independent.

Assume that \( \tilde{G} \) is lower triangular. From proposition 5.1, it follows that we may assume that \( G_1 = G_2 = 0 \). Since the last four components of \( G \), and hence those of \( G(Tx) \) as well, are linearly independent, it follows from \( 0 = \tilde{G}_1 = (T^{-1}_1)G(Tx) \) that the last four coordinates of \( (T^{-1}_1) \) are zero. Similarly, the last four coordinates of \( (T^{-1}_2) \) are zero. Since \( G \) is lower triangular, we have \( G_3 \in \mathbb{C}[x_1, x_2] \), whence \( (T^{-1}_2)G_3 = G_3(T^{-1}_1x) \in \mathbb{C}[x_1, x_2] \) as well.

Looking at \( \frac{\partial}{\partial x_3} G_i \) for all \( i \), it follows that \( (T^{-1}_2)G_3 \in \mathbb{C}[x_1, x_2] \), if and only if \( (T^{-1}_3) \) is of the form
\[ T^{-1}_3 = (\mu_1 \mu_2 \mu_3 0 0 0) \]
Assume \( \tilde{G}_3 \) is the square of a linear form. Then \( (T^{-1}_3)G_3 \) is such a square as well. This requires \( \mu_3 = 0 \), so the first three rows of \( T^{-1}_3 \) are dependent. Contradiction, so \( \tilde{G}_3 \) is not the square of a linear form.

In [12, Th. 8.4.2], a special cubic linear map is given that is not linearly triangularizable; the proof follows from [12, Th 7.4.4] and [12, Th 8.3.2]. Another
power linear map that is not linearly triangularizable is

\[
H = \begin{pmatrix}
0 \\
0 \\
(x_1 + x_5 - x_6 + x_7 - x_9)^2 \\
(x_2 + x_5 - x_6 + x_7 - x_9)^2 \\
(x_2 + x_3 - x_8)^2 \\
(x_3 - x_8)^2 \\
(x_4 - x_8)^2 \\
(x_5 - x_6 + x_7 - x_9)^2 \\
(x_1 + x_4 - x_8)^2
\end{pmatrix}
\]

The proof that this quadratic linear map cannot linearly be triangularized at all uses the same techniques as above, and is left as an exercise to the reader. Since for a triangular special homogeneous map \( x + H \), either the first or the last component of \( H \) is zero, triangularizability of a power linear map \( H \) implies that its components are linearly dependent over \( \mathbb{C} \). So one can ask whether the components of \( H \) need to be linearly dependent. This is not the case: in [3], the second author shows that there exists a cubic linear counterexample to this linear dependence problem in dimension 53.

References


