

1 The computation of $G_n(\mathbb{Q}_p)$

1.1 The computation of the first block M_{11}

Proposition 1.1.1. *Let $x = \sum_{i=1}^{n-1} \lambda_i e_{i,i+1}$, where $\lambda_i \in \mathbb{Q}_p$ are not all zero. Then $\dim \mathcal{C}_{\gamma_1/\gamma_3}(x)/\gamma_2 = \mathfrak{l}(x) + \mathfrak{m}(x)$, where $\mathfrak{l}(x)$ is the number of sequences of consecutive non-zero coefficients of the form $\lambda_j, \lambda_{j+1}, \dots, \lambda_{j+k-1}, \lambda_{j+k}$ and $\lambda_{j-1} = \lambda_{j+k+1} = 0$ (that is, the sequences are separated by one or more zero coefficients)¹, and $\mathfrak{m}(x)$ is the number of zero coefficients $\lambda_j = 0$, such that also $\lambda_{j-1} = \lambda_{j+1} = 0$.*

Proof. Let $y = \sum_{i=1}^{n-1} \mu_i e_{i,i+1}$, where $\mu_i \in \mathbb{Q}_p$, be an element in the quotient γ_1/γ_2 . For every $1 \leq i \leq n-1$, denote by (\mathfrak{C}_i) the constraint equation $[\lambda_i e_{i,i+1}, \mu_{i+1} e_{i+1,i+2}] - [\lambda_{i+1} e_{i+1,i+2}, \mu_i e_{i,i+1}] = (\lambda_i \mu_{i+1} - \lambda_{i+1} \mu_i) e_{i,i+2} = 0$, and it is clear that $y \in \mathcal{C}_{\gamma_1/\gamma_3}(x)/\gamma_2$ if and only if all the (\mathfrak{C}_i) constraints are satisfied. We observe that each μ_i participates in two constraints, (\mathfrak{C}_{i-1}) and (\mathfrak{C}_i) , that is, $\lambda_{i-1} \mu_i - \lambda_i \mu_{i-1} = \lambda_i \mu_{i+1} - \lambda_{i+1} \mu_i = 0$. If $\lambda_i = 0$, then $\lambda_i \mu_{i-1} = \lambda_i \mu_{i+1} = 0$, hence by constraint (\mathfrak{C}_{i-1}) we have that $\lambda_{i-1} \mu_i = 0$, and by constraint (\mathfrak{C}_i) we have that $\lambda_{i+1} \mu_i = 0$. Hence, if either λ_{i-1} or λ_{i+1} are non-zero, then $\mu_i = 0$. But if $\lambda_{i-1} = \lambda_{i+1} = 0$, then both constraints are satisfied for any choice of μ_i , which increases $\dim \mathcal{C}_{\gamma_1/\gamma_3}(x)/\gamma_2$ by 1. We need to prove that for any sequence of k consecutive zero coefficients of x , where $k \geq 3$, that is² $\lambda_{j+1} = \lambda_{j+2} = \dots = \lambda_{j+k} = 0$, for $1 \leq j \leq n-2$, we have that the sequence $\mu_{j+2}, \mu_{j+3}, \dots, \mu_{j+k-1}$ of $k-2$ consecutive coefficients of y is made of scalars of any choice, thus $\dim \mathcal{C}_{\gamma_1/\gamma_3}(x)/\gamma_2$ is increased by $k-2$. We prove that by simple induction on k . For $k = 3$, we just proved that if $\lambda_{i-1} = \lambda_i = \lambda_{i+1} = 0$, then μ_i can be any scalar. For $k + 1$, we look at the sequence of $k + 1$ zero coefficients, $\lambda_{j+1} = \lambda_{j+2} = \dots = \lambda_{j+k} = \lambda_{j+k+1} = 0$. By constraints (\mathfrak{C}_{j+k-1}) and (\mathfrak{C}_{j+k}) , we have that $\lambda_{j+k-1} \mu_{j+k} - \lambda_{j+k} \mu_{j+k-1} = \lambda_{j+k} \mu_{j+k+1} - \lambda_{j+k+1} \mu_{j+k} = 0$, and since $\lambda_{j+k-1} = \lambda_{j+k} = \lambda_{j+k+1} = 0$, we have that μ_{j+k} can be any scalar, as we proved earlier. By the assumption, we have that all $k-2$ previous coefficients, that is $\mu_{j+2}, \dots, \mu_{j+k-1}$ can also be any scalars, so in total the whole sequence of $k-1 = (k+1)-2$ coefficients of y can be any scalars, which proves the induction step. Suppose that we have m sequences of three or more consecutive zero coefficients in x , whose lengths are k_1, k_2, \dots, k_m ,

¹We extend our notation of indices, to include also the case where $j = 1$ or $j+k = n-1$, and define that $\lambda_{j-1} = \lambda_0 = 0$ or $\lambda_{j+k+1} = \lambda_n = 0$, respectively

²Here again, we consider the non-existent $\lambda_0 = \lambda_n = 0$ as part of the sequence

then $\mathbf{m}(x) = \sum_{l=1}^m k_l - 2m$ is the total number of zero coefficients $\lambda_j = 0$ such that also $\lambda_{j-1} = \lambda_{j+1} = 0$, as proposed. Using again the two consecutive constraints, (\mathfrak{C}_{i-1}) and (\mathfrak{C}_i) , suppose now that $\lambda_i \neq 0$. If $\lambda_{i-1} = 0$, then by constraint (\mathfrak{C}_{i-1}) we must have that $\mu_{i-1} = 0$, but if $\lambda_{i-1} \neq 0$, then by this constraint we have $\mu_i = \frac{\lambda_i \mu_{i-1}}{\lambda_{i-1}}$, which means that μ_i depends on μ_{i-1} . Precisely the same way for constraint (\mathfrak{C}_i) , we have that if $\lambda_{i+1} = 0$ then $\mu_{i+1} = 0$, otherwise $\mu_{i+1} = \frac{\lambda_{i+1} \mu_i}{\lambda_i}$, which means that μ_{i+1} depends on μ_i ,

and if also $\lambda_{i-1} \neq 0$, then $\mu_{i+1} = \frac{\lambda_{i+1} \frac{\lambda_i \mu_{i-1}}{\lambda_{i-1}}}{\lambda_i} = \frac{\lambda_{i+1} \mu_{i-1}}{\lambda_{i-1}}$, which means that both μ_{i+1} and μ_i depend on μ_{i-1} . We need to prove this is true for any sequence of k consecutive non-zero coefficients of x , that is, for a given sequence of coefficients, $\lambda_{j+1}, \lambda_{j+2}, \dots, \lambda_{j+k}$, where $1 \leq j \leq n-1$, we need to prove that μ_{j+1} can be any scalar, while $\mu_{j+2}, \mu_{j+3}, \dots, \mu_{j+k}$ all depend on μ_{j+1} . Here again, we use a simple induction on k . For $k = 1, 2, 3$, we already proved this. For $k+1$, we look into a sequence of $k+1$ consecutive non-zero coefficients of x , that is $\lambda_{j+1}, \dots, \lambda_{j+k}, \lambda_{j+k+1}$. By constraint (\mathfrak{C}_{j+k}) we have $\lambda_{j+k} \mu_{j+k+1} - \lambda_{j+k+1} \mu_{j+k} = 0$, and since $\lambda_{j+k} \neq 0$, we have $\mu_{j+k+1} = \frac{\lambda_{j+k+1} \mu_{j+k}}{\lambda_{j+k}}$, but by the assumption, $\mu_{j+k} = \frac{\lambda_{j+k} \mu_{j+k-1}}{\lambda_{j+k-1}} = \frac{\lambda_{j+k}}{\lambda_{j+k-1}} \frac{\lambda_{j+k-1} \mu_{j+k-2}}{\lambda_{j+k-2}} = \frac{\lambda_{j+k}}{\lambda_{j+k-1}} \frac{\lambda_{j+k-1}}{\lambda_{j+k-2}} \frac{\lambda_{j+k-2} \mu_{j+k-3}}{\lambda_{j+k-3}} = \dots = \frac{\lambda_{j+k} \mu_{j+1}}{\lambda_{j+1}}$, hence $\mu_{j+k+1} = \frac{\lambda_{j+k+1} \mu_{j+k}}{\lambda_{j+k}} = \frac{\lambda_{j+k+1} \lambda_{j+k-1} \mu_{j+k-2}}{\lambda_{j+k-1} \lambda_{j+k-2}} = \frac{\lambda_{j+k+1} \lambda_{j+k-1}}{\lambda_{j+k-1} \lambda_{j+k-2}} \frac{\lambda_{j+k-2} \mu_{j+k-3}}{\lambda_{j+k-3}} = \dots = \frac{\lambda_{j+k+1} \mu_{j+1}}{\lambda_{j+1}}$, which proves the induction step. Looking again at (\mathfrak{C}_{i-1}) and (\mathfrak{C}_i) , we observe that if λ_{i-1} and λ_{i+1} are non-zero and $\lambda_i = 0$, then $\lambda_i \mu_{i-1} = \lambda_i \mu_{i+1} = 0$, hence by constraint (\mathfrak{C}_{i-1}) we have that $\lambda_{i-1} \mu_i = 0$, and by constraint (\mathfrak{C}_i) we have that $\lambda_{i+1} \mu_i = 0$, so $\mu_i = 0$ by both constraints, which means that there is no dependency between μ_{i+1} and μ_{i-1} . This shows that any zero coefficient between two non-zero coefficients of x creates two separate sequences, each sequences increases $\dim \mathcal{C}_{\gamma_1/\gamma_3}(x)/\gamma_2$ by 1, hence, if we have l sequences of consecutive non-zero coefficients of x , they increase $\dim \mathcal{C}_{\gamma_1/\gamma_3}(x)/\gamma_2$ by l , and we denote $\mathfrak{l}(x) = l$. All this shows that $\dim \mathcal{C}_{\gamma_1/\gamma_3}(x)/\gamma_2 = \mathfrak{l}(x) + \mathbf{m}(x)$, as proposed. \square

Corollary 1.1.2. *Let $\mathcal{L}_{n,p}$ be the \mathbb{Q}_p -Lie algebra associated with $\mathcal{U}_n(\mathbb{Z})$. If $n \geq 5$, then $\dim \mathcal{C}_{\gamma_1/\gamma_3}(x) = \dim \gamma_1/\gamma_3 - 1$ if and only if $x \in \{\lambda e_{12} + \gamma_2 \mathcal{L}_{n,p}\}$ or $x \in \{\lambda e_{n-1,n} + \gamma_2 \mathcal{L}_{n,p}\}$, for a non-zero scalar $\lambda \in \mathbb{Q}_p$. If $n = 4$, then $\dim \mathcal{C}_{\gamma_1/\gamma_3}(x) = \dim \gamma_1/\gamma_3 - 1$ if and only if $x \in \{\lambda e_{12} + \mu e_{34} + \gamma_2 \mathcal{L}_{n,p}\}$, for $\lambda, \mu \in \mathbb{Q}_p$ not both zero.*

Proof. We recall first that for any algebra $\mathcal{L}_{n,p}$, the first two elements of the lower central series, namely γ_1/γ_2 and γ_2/γ_3 , are of sizes $n-1$ and $n-2$,

respectively. Consider the Lie brackets operation $[x_1, x_2]$, where $x_1 \in \gamma_1/\gamma_2$ and $x_2 \in \gamma_2/\gamma_3$, or the opposite, then $[x_1, x_2]$ can be either zero, or $[x_1, x_2] \in \gamma_3$, which means that if we consider the centralizer of some $x \in \mathcal{L}_{n,p}$ in γ_1/γ_3 , then any element $y \in \gamma_2/\gamma_3$ would either commute with x or yield an element in γ_3 , which also means that it commutes with x in γ_1/γ_3 . This shows that $\dim \mathcal{C}_{\gamma_1/\gamma_3}(x) \geq \dim \gamma_2/\gamma_3 = n - 2$. Suppose that $x = \lambda_1 e_{12} + z$ or $x = \lambda_{n-1} e_{n-1,n} + z$, where $z \in \gamma_2 \mathcal{L}_{n,p}$, then looking only at the elements of γ_1/γ_2 in the linear combination that forms x , we have one sequence of one non-zero coefficient, hence $\mathbf{l}(x) = 1$, and one sequence of $n - 1 - 1 = n - 2$ zero coefficients of x , hence we have³ that $\mathbf{m}(x) = n - 2 - 1 = n - 3$. By 1.1.1 we have that $\dim \mathcal{C}_{\gamma_1/\gamma_3}(x)/\gamma_2 = \mathbf{l}(x) + \mathbf{m}(x) = 1 + (n - 3) = n - 2$. Adding all the elements of γ_2/γ_3 , we have that $\dim \mathcal{C}_{\gamma_1/\gamma_3}(x) = (n - 2) + (n - 2) = 2n - 4 = (n - 1) + (n - 2) - 1 = \dim \gamma_1/\gamma_2 + \dim \gamma_2/\gamma_3 - 1 = \dim \gamma_1/\gamma_3 - 1$, as proposed. To prove the opposite direction, we assume that $\dim \mathcal{C}_{\gamma_1/\gamma_3}(x) = \dim \gamma_1/\gamma_3 - 1 = 2n - 4$, and since we already know that all the elements of $\dim \gamma_2/\gamma_3$ are in the centralizer of x , we have that $\dim \mathcal{C}_{\gamma_1/\gamma_3}(x)/\gamma_2 = \dim \mathcal{C}_{\gamma_1/\gamma_3}(x) - \dim \gamma_2/\gamma_3 = (2n - 4) - (n - 2) = n - 2 = (n - 1) - 1 = \dim \gamma_1/\gamma_2 - 1$. Suppose that either $x = \lambda_i e_{i,i+1} + z$ where $1 < i < n - 1$, or $x = \lambda_{i_1} e_{i_1,i_1+1} + \dots + \lambda_{i_m} e_{i_m,i_m+1}$ where we denote the number of γ_1/γ_2 coefficients⁴ by $2 \leq m \leq n - 1$, in both cases $z \in \gamma_2 \mathcal{L}_{n,p}$. In the first case, we have that $\mathbf{l}(x) = 1$, because there is only one non-zero coefficient of x in γ_1/γ_2 , and we have two sequences of zero coefficients of x , that is $\lambda_0 = \lambda_1 = \lambda_2 = \dots = \lambda_{i-2} = \lambda_{i-1} = 0$ and $\lambda_{i+1} = \lambda_{i+2} = \lambda_{i+3} = \dots = \lambda_{n-2} = \lambda_{n-1} = \lambda_n = 0$, which means we have a sequence of zeros of length $(i - 1) + 1 = i$ and a sequence of length $(n - 1) - i + 1 = n - i$, hence by 1.1.1 we have⁵ that $\mathbf{m}(x) \leq (i - 2) + (n - i - 2) = n - 4$, which means that $\dim \mathcal{C}_{\gamma_1/\gamma_3}(x)/\gamma_2 = \mathbf{l}(x) + \mathbf{m}(x) \leq 1 + (n - 4) = n - 3 = (n - 1) - 2 = \dim \gamma_1/\gamma_2 - 2$. Adding all the elements of γ_2/γ_3 , we have that $\dim \mathcal{C}_{\gamma_1/\gamma_3}(x) = \dim \mathcal{C}_{\gamma_1/\gamma_3}(x)/\gamma_2 + \dim \gamma_2/\gamma_3 = (n - 3) + (n - 2) = 2n - 5 < 2n - 4$, which contradicts the assumption. Suppose that x is of the second form, then x may have one sequence of k non-zero coefficients, where $k > 1$, or

³Again, we consider also $\lambda_0 = 0$ and $\lambda_n = 0$, hence the sequence of zero coefficients is either $\lambda_2 = \lambda_3 = \dots = \lambda_{n-2} = \lambda_{n-1} = \lambda_n = 0$ if $\lambda_1 \neq 0$, or $\lambda_0 = \lambda_1 = \lambda_2 = \dots = \lambda_{n-3} = \lambda_{n-2} = 0$, if $\lambda_{n-1} \neq 0$, which means that the length of the entire sequence of zero coefficients is not $n - 2$ but $n - 1$, therefore by 1.1.1 we have that $\mathbf{m}(x) = n - 1 - 2 = n - 3$

⁴In words, x has at least two non-zero coefficients in γ_1/γ_2

⁵Here, and in all the following options, $\mathbf{m}(x)$ has an upper bound which depend on the number of consecutive zero coefficients of x , because if any of these sequences is of length k , where $k < 3$, then $\mathbf{m}(x) = k - 2 \leq 0$

have two or more sequences of non-zero coefficients. In the case that x has one sequence of k non-zero coefficients, $\mathbf{l}(x) = 1$, and the number of consecutive zero coefficients is either less or equal⁶ to $(n-1) - k + 1 = n - k$, which results in $\mathbf{m}(x) \leq n - k - 2$, if the sequence of non-zero coefficients contains⁷ either λ_1 or λ_{n-1} , or the number of consecutive zero coefficients is divided into two separate sequences with a total number of consecutive zeros which is less or equal to $(n-1) - k + 2 = n - k + 1$, which results in $\mathbf{m}(x) \leq n - k + 1 - 4 = n - k - 3$, in the case that the sequence of non-zero coefficients of x does not contains either λ_1 or λ_{n-1} , which means that $\mathbf{l}(x) + \mathbf{m}(x) \leq 1 + (n - k - 2) = n - k - 1$, and since $k > 1$, we have that $\dim \mathcal{C}_{\gamma_1/\gamma_3}(x)/\gamma_2 = \mathbf{l}(x) + \mathbf{m}(x) \leq n - 2 - 1 = n - 3 = (n-1) - 2$, which again contradicts the assumption. Suppose that x has l sequences of non-zero coefficients in γ_1/γ_2 , of lengths k_1, k_2, \dots, k_l , then $\mathbf{l}(x) = l$, and the number of zeros is $n - 1 - \sum_{j=1}^l k_j$. Considering the two options from earlier, whether any of the sequences of non-zero coefficients contains λ_1 or λ_{n-1} , or does not contain either of them, we observe that $\mathbf{m}(x) \leq$

Looking into the elements of γ_1/γ_2 itself, then by 1.1.1, we have that $\dim \mathcal{C}_{\gamma_1/\gamma_3}(x)/\gamma_2 =$

Let $z = \lambda_{j,j+2}e_{j,j+2}$, where $1 \leq j \leq n-2$ and $\lambda_{j,j+2} \in \mathbb{Q}_p$, then for every $w \in \gamma_1/\gamma_3$, either z commutes with w or $[z, w] \in \gamma_3\mathcal{L}_{n,p}$, which means that $\lambda_{j,j+2}e_{j,j+2} \in \mathcal{C}_{\gamma_1/\gamma_3}$, for every $1 \leq j \leq n-2$. Hence, $\gamma_2/\gamma_3 = \langle e_{13}, e_{24}, \dots, e_{n-2,n} \rangle \subset \mathcal{C}_{\gamma_1/\gamma_3}(x)$. Therefore, we only need to discuss elements of the quotient γ_1/γ_2 , for the purpose of this proof. Suppose that $x = \lambda_1 e_{12} + z$, where $z \in \gamma_2\mathcal{L}_{n,p}$, then we have one sequence of non-zero coefficients, namely λ_1 , and we have $n-2$ zero coefficients $\lambda_2 = \lambda_3 = \dots = \lambda_{n-1} = 0$, from which $n-3$ are between two other zeros. Hence, by 1.1.1, we have that $\dim \mathcal{C}_{\gamma_1/\gamma_2}(x) = 1 + (n-3) = n-2 = (n-1) - 1 = \dim \gamma_1/\gamma_2 - 1$. Similarly, the same goes also for $x = \lambda_{n-1} e_{n-1,n} + z$. Suppose that $\dim \mathcal{C}_{\gamma_1/\gamma_2}(x) = \dim \gamma_1/\gamma_2 - 1$, but $x = \sum_{i=1}^{n-1} \lambda_i e_{i,i+1}$, such that either of the following options is true:

1. there is more than one sequence of consecutive non-zero coefficients in the linear combination that forms x .
2. there is one sequence of consecutive non-zero coefficients, but at least one of those coefficients has index $2 \leq j \leq n-2$, meaning it is not λ_1

⁶

⁷That is, $x = \lambda_1 e_{12} + \lambda_2 e_{23} + \dots + \lambda_{k,k+1} e_{k,k+1}$ or $x = \lambda_{n-k} e_{n-k,n-k+1} + \lambda_{n-k+1} e_{n-k+1,n-k+2} + \dots + \lambda_{n-1} e_{n-1,n}$

nor λ_{n-1} .

For the second option, we start by fixing one index $2 \leq j \leq n-2$, and assume that $x = \lambda_j e_{j,j+1}$. The number of zero coefficients in x is $n-1-1 = n-2$, but λ_j and the zeros in indices $j-1, j+1$ are neighboring, hence $m_1 = n-2-2 = n-4$, and then $\dim \mathcal{C}_{\gamma_1/\gamma_2}(x) = l_1 + m_1 = 1 + n-4 = n-3 < n-2 = \dim \gamma_1/\gamma_2 - 1$. We denote by k the length of the sequence of consecutive non-zero parameters, and prove that for any $k > 0$, where at least one non-zero coefficient λ_j lies in $2 \leq j \leq n-2$, $\dim \mathcal{C}_{\gamma_1/\gamma_2}(x) < n-2$, by simple induction on k . For $k = 1$, we have just shown that. For $k > 1$, there are $k-1$ additional zeros that are replaced by non-zero coefficients, where except for λ_{j-1} and λ_{j+1} , all the other zeros were originally lying between two other zeros. If the original sequence was $\lambda_2 e_{23}$ or $\lambda_{n-2} e_{n-2,n-1}$, and the new sequence is $\lambda_1 e_{12}, \lambda_2 e_{23}$ or $\lambda_{n-2} e_{n-2,n-1}, \lambda_{n-1} e_{n-1,n}$, respectively, then $m_k = m_1$, but clearly, in any other case, $m_k < m_1$, while $l_k = l_1 = 1$ at any case. by the assumption, for the original sequence, $\dim \mathcal{C}_{\gamma_1/\gamma_2}(x) = l_1 + m_1 < n-2$, hence for the new sequence, $\dim \mathcal{C}_{\gamma_1/\gamma_2}(x) = l_k + m_k \leq l_1 + m_1 = n-3 < n-2$. Now we check the first option, starting from the case where $x = \lambda_1 e_{12} + \lambda_{n-1} e_{n-1,n}$. In this case, $l_2 = 2$ and the number of zeros is $n-1-2 = n-3$, but λ_1 and the zero in index 2 are neighboring, and so are λ_{n-1} and the zero in index $n-2$, hence $m_2 = n-3-2 = n-5$ zeros are lying between two other zeros, therefore $\dim \mathcal{C}_{\gamma_1/\gamma_2}(x) = l_2 + m_2 = n-5+2 = n-3 < n-2$. if we add another non-zero coefficient, then it must lie in some index $2 \leq j \leq n-2$, for which we have already proved that $\dim \mathcal{C}_{\gamma_1/\gamma_2}(x) < n-2$, which completes the proof for $n \geq 5$. For $n = 4$, we can check explicitly. Assume $x = \lambda e_{12} + \mu e_{34}$, denote an element in the centralizer of x by $y = \rho e_{12} + \tau e_{23} + \nu e_{34}$, and we observe that $[x, y] = [\lambda e_{12}, \tau e_{23}] + [\mu e_{34}, \tau e_{23}] = \lambda \tau e_{13} - \tau \mu e_{24} = 0$, hence $\tau = 0$, while $\rho = *$ and $\nu = *$, so $\dim \mathcal{C}_{\gamma_1/\gamma_2}(x) = 2 = \dim \gamma_1/\gamma_2 - 1$, as requested, and it is readily seen that even if either $\lambda = 0$ or $\mu = 0$, but not both, then τ still has to be zero, in order to satisfy either $\tau \mu = 0$ or $\lambda \tau = 0$, respectively, and ρ, ν can still be anything, which means that in either case, where the coefficient of e_{23} is zero but $x \neq 0$, we have $\dim \mathcal{C}_{\gamma_1/\gamma_2}(x) = 2$. Assume $\dim \mathcal{C}_{\gamma_1/\gamma_2}(x) = \dim \gamma_1/\gamma_2 - 1 = 3 - 1 = 2$, then if x is not of the suggested form, it means that $x = \lambda e_{12} + \sigma e_{23} + \mu e_{34}$, where $\sigma \neq 0$ and either λ or μ or both can be zero. If $x = \lambda e_{12} + \sigma e_{23} + \mu e_{34}$ and all coefficients are non-zero, then for every $y \in \mathcal{C}_{\gamma_1/\gamma_2}(x)$ denoted by $y = \rho e_{12} + \tau e_{23} + \nu e_{34}$, we have $[x, y] = [\lambda e_{12}, \tau e_{23}] + [\sigma e_{23}, \rho e_{12}] + [\sigma e_{23}, \nu e_{34}] + [\mu e_{34}, \tau e_{23}] = (\lambda \tau - \sigma \rho) e_{13} + (\sigma \nu - \mu \tau) e_{24}$, hence $\tau = \frac{\sigma}{\lambda} \rho$ and $\nu = \frac{\mu}{\sigma} \tau = \frac{\mu}{\sigma} \frac{\sigma}{\lambda} \rho = \frac{\mu}{\lambda} \rho$, but this means

that $\dim \mathcal{C}_{\gamma_1/\gamma_2}(x) = 1$, because both τ and ν depend on ρ . If either λ or μ or both are zero, then either $\sigma\rho$ or $\sigma\mu$ or both are zero, which means that ρ or ν or both are zero, since $\sigma \neq 0$, but this means that either $y = \tau e_{23} + \frac{\mu}{\sigma} \tau e_{34}$ or $y = \frac{\lambda}{\sigma} \tau e_{12} + \tau e_{23}$ or $y = \tau e_{23}$, respectively. Therefore, in either case, where $\sigma \neq 0$, we have $\dim \mathcal{C}_{\gamma_1/\gamma_2}(x) = 1$, which completes the proof for $n = 4$. \square

Corollary 1.1.3. *Let $\mathcal{L}_{n,p}$ be a \mathbb{Q}_p -Lie algebra, where $n \geq 4$, and let $\varphi \in G_n(\mathbb{Q}_p)$ be an $\mathcal{L}_{n,p}$ -automorphism, then $\varphi_{11}(e_{12}) = \lambda_1 e_{12}$ and $\varphi_{11}(e_{n,n-1}) = \lambda_{n-1} e_{n-1,n}$, or $\varphi_{11}(e_{12}) = \lambda_{n-1} e_{n-1,n}$ and $\varphi_{11}(e_{n,n-1}) = \lambda_1 e_{1,2}$.*

Proof. We look at the centralizer of e_{12} in the quotient γ_1/γ_3 , namely $\mathcal{C}_{\gamma_1/\gamma_3}(e_{12})$. Clearly, for any $e_{i,i+2} \in \gamma_2/\gamma_3$, we have that $[e_{12}, e_{i,i+2}]$ is either zero, or $i = 2$ and then $[e_{12}, e_{24}] = e_{14} \in \gamma_3 \mathcal{L}_{n,p}$, which vanishes in the quotient γ_1/γ_3 , which means that in either case it is zero in this quotient. Therefore, we look only at elements $e_{i,i+1} \in \gamma_1/\gamma_2$. It is readily seen that every element of the form $e_{i,i+1}$ where $i \neq 2$ commutes with e_{12} , hence $\mathcal{C}_{\gamma_1/\gamma_2}(e_{12}) = \langle e_{12}, e_{34}, e_{45}, \dots, e_{n-2,n-1}, e_{n-1,n} \rangle$, so $\dim \mathcal{C}_{\gamma_1/\gamma_2}(e_{12}) = \dim \gamma_1/\gamma_2 - 1$, but since φ_{11} is an automorphism, it must preserve the dimension of the centralizer, meaning $\dim \mathcal{C}_{\gamma_1/\gamma_2}(\varphi_{11}(e_{12})) = \dim \mathcal{C}_{\gamma_1/\gamma_2}(e_{12}) = \dim \gamma_1/\gamma_2 - 1$. But by corollary 1.1.2, if $n \geq 5$, then $\varphi_{11}(e_{12}) = \lambda e_{12}$ or $\varphi_{11}(e_{12}) = \lambda e_{n-1,n}$, and it is readily seen that the same applies also for $\varphi_{11}(e_{n-1,n})$, and since φ is injective, then clearly, if $\varphi_{11}(e_{12}) = \lambda e_{12}$ then $\varphi_{11}(e_{n-1,n}) = \lambda e_{n-1,n}$, and if $\varphi_{11}(e_{12}) = \lambda e_{n-1,n}$ then $\varphi_{11}(e_{n-1,n}) = \lambda e_{12}$. If $n = 4$, then by the same corollary, $\varphi_{11}(e_{12}) = \lambda e_{12} + \mu e_{34}$, where λ and μ are not both zero, which means that the same proof does not hold. Therefore, we now look at the centralizer of e_{12} in the algebra $\mathcal{L}_{4,p}$ itself. We denote by $\mathcal{C}_{\mathcal{L}_{4,p}}(e_{12})$ the centralizer of e_{12} in the algebra, which is $\mathcal{C}_{\mathcal{L}_{4,p}}(e_{12}) = \langle e_{12}, e_{34}, e_{13}, e_{14} \rangle$, so $\dim \mathcal{C}_{\mathcal{L}_{4,p}}(e_{12}) = 4$. Denote by $x = \varphi(e_{12}) = \lambda_{12} e_{12} + \lambda_{23} e_{23} + \lambda_{34} e_{34} + \lambda_{13} e_{13} + \lambda_{24} e_{24} + \lambda_{14} e_{14} \in \mathcal{L}_{4,p}$, and denote by $y = \mu_{12} e_{12} + \mu_{23} e_{23} + \mu_{34} e_{34} + \mu_{13} e_{13} + \mu_{24} e_{24} + \mu_{14} e_{14} \in \mathcal{C}_{\mathcal{L}_{4,p}}(e_{12})$, an element in the centralizer of e_{12} , hence $[x, y] = (\lambda_{12} \mu_{23} - \lambda_{23} \mu_{12}) e_{13} + (\lambda_{23} \mu_{34} - \lambda_{34} \mu_{23}) e_{24} + (\lambda_{12} \mu_{24} - \lambda_{24} \mu_{12} + \lambda_{13} \mu_{34} - \lambda_{34} \mu_{13}) e_{14} = 0$. Assume all the coefficients of the linear combination that forms x are non-zero. Then, as seen earlier, we have that $\mu_{23} = \frac{\lambda_{23}}{\lambda_{12}} \mu_{12}$, and $\mu_{34} = \frac{\lambda_{34}}{\lambda_{23}} \mu_{23} = \frac{\lambda_{34}}{\lambda_{23}} \frac{\lambda_{23}}{\lambda_{12}} \mu_{12} = \frac{\lambda_{34}}{\lambda_{12}} \mu_{12}$, and also $\lambda_{12} \mu_{24} - \lambda_{24} \mu_{12} + \lambda_{13} \mu_{34} - \lambda_{34} \mu_{13} = 0$, which means that $\mu_{24} = \frac{\lambda_{24} \mu_{12} + \lambda_{13} \mu_{34} - \lambda_{34} \mu_{13}}{\lambda_{12}} = \frac{\lambda_{24} \mu_{12} + \lambda_{13} \frac{\lambda_{34}}{\lambda_{12}} \mu_{12} - \lambda_{34} \mu_{13}}{\lambda_{12}}$, hence we can choose freely μ_{12} , μ_{13} and μ_{14} , while μ_{23} and μ_{34} depend on μ_{12} , and μ_{24} depends on μ_{12} and μ_{13} , which means that $\dim \mathcal{C}_{\mathcal{L}_{4,p}}(y) = 3 < 4 = \dim \mathcal{C}_{\mathcal{L}_{4,p}}(e_{12})$. Assume that all the coefficients of x are non-zero, except for $\lambda_{23} = 0$, then

$\lambda_{12}\mu_{23}$ and $\lambda_{34}\mu_{23}$ must vanish, hence $\mu_{23} = 0$, but then μ_{34} does not depend on μ_{23} , which implies that it does not depend on μ_{12} either, and can be chosen freely, hence there is no change in the dimension of $\mathcal{C}_{\mathcal{L}_{4,p}}(e_{12})$ from the general case. Now we assume $x = \lambda_{12}e_{12} + z$, where $z \in \gamma_2\mathcal{L}_{4,p}$, and observe the three equations from above with the current assumption. The second equation $\lambda_{23}\mu_{34} - \lambda_{34}\mu_{23} = 0$ completely falls, which from the other two we obtain that $\lambda_{12}\mu_{23}$ and $\lambda_{12}\mu_{24}$ must vanish, which means that $\mu_{23} = \mu_{24} = 0$, while μ_{12} , μ_{34} , μ_{13} and μ_{14} can be chosen freely, which means that $\dim \mathcal{C}_{\mathcal{L}_{4,p}}(y) = 4 = \dim \mathcal{C}_{\mathcal{L}_{4,p}}(e_{12})$. One checks that the same applies also for $\varphi(e_{12}) = \lambda_{34}e_{34} + z$, and that no other linear combination of x satisfies that $\dim \mathcal{C}_{\mathcal{L}_{4,p}}(\varphi(e_{12})) = \dim \mathcal{C}_{\mathcal{L}_{4,p}}(e_{12})$. \square