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On the rational symplectic group

Yves Benoist

Abstract

We give a short proof of an elementary classical result: any rational symplectic matrix can be put in diagonal form after right and left multiplication by integral symplectic matrices. We also give a new proof for its extension to Chevalley groups due to Steinberg by using the Cartan-Bruhat-Tits decomposition over p -adic fields.

1 Introduction

In this expository paper I present a short proof of a classical theorem I needed in [1]: a decomposition of the group $\mathrm{Sp}(n, \mathbb{Q})$ of symplectic matrices with rational coefficients that gives a parametrization of the double quotient $\mathrm{Sp}(n, \mathbb{Z}) \backslash \mathrm{Sp}(n, \mathbb{Q}) / \mathrm{Sp}(n, \mathbb{Z})$ where $\mathrm{Sp}(n, \mathbb{Z})$ is the subgroup of symplectic matrices with integral coefficients.

This decomposition which can already be found in [15] is a symplectic version of the “adapted basis theorem” for \mathbb{Z} -modules, or of the “Smith normal form” for integral matrices.

In Section 2 we state precisely this decomposition that we call the “symplectic Smith normal form”.

In Section 3 we explain the analogy with the Cartan-Bruhat-Tits decomposition.

In Section 4 we recall the relevance of Bruhat-Tits buildings in this kind of decomposition.

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In Section 5 we give an elementary proof of the symplectic Smith normal form.

In Section 6 we give a non-elementary proof of the symplectic Smith normal form that will be applied to other simply-connected split semisimple algebraic groups \mathbf{G} defined over \mathbb{Q} in the last section. Indeed we explain how this symplectic Smith normal form can be deduced from the Cartan-Bruhat-Tits decomposition together with the strong approximation theorem.

In Section 7 we explain the extension due to Steinberg of the Smith normal form to the simply-connected \mathbb{Q} -split groups, see Theorem 7.1.

The last two sections are a concrete illustration of a classical strategy: if you want to prove a theorem over a global field, prove it first over local fields and then use a local-global principle.

I would like to thank Hee Oh for a very helpful comment on a first draft of this note.

2 The symplectic Smith normal form

For any commutative ring R with unity, we denote by $\mathrm{Sp}(n, R)$ the symplectic group with coefficients in R . This group is the stabilizer of the symplectic form ω on R^{2n} given by, for all x, y in R^{2n} ,

$$\omega(x, y) = {}^t x J y$$

where $J = \begin{pmatrix} \mathbf{0} & \mathbf{1}_n \\ -\mathbf{1}_n & \mathbf{0} \end{pmatrix}$. Equivalently, one has

$$\mathrm{Sp}(n, R) := \{g \in \mathrm{GL}(2n, R) \mid {}^t g J g = J\},$$

If we write the elements of the symplectic group as block matrices with blocks of size n , one has

$$\mathrm{Sp}(n, R) = \left\{ g = \begin{pmatrix} \alpha & \beta \\ \gamma & \delta \end{pmatrix} \mid {}^t \alpha \gamma = {}^t \gamma \alpha, \quad {}^t \beta \delta = {}^t \delta \beta, \quad {}^t \alpha \delta - {}^t \gamma \beta = \mathbf{1}_n \right\}.$$

Theorem 2.1. *Let $g \in \mathrm{Sp}(n, \mathbb{Q})$. Then there exist two matrices σ and σ' in $\mathrm{Sp}(n, \mathbb{Z})$ and a positive integral diagonal matrix $\mathbf{d} = \mathrm{diag}(d_1, \dots, d_n)$ with $d_1 | d_2 | \dots | d_n$, and such that*

$$g = \sigma \begin{pmatrix} \mathbf{d} & \mathbf{0} \\ \mathbf{0} & \mathbf{d}^{-1} \end{pmatrix} \sigma'.$$

The condition that the coefficients d_j are positive integers with d_1 dividing d_2 , with d_2 dividing d_3, \dots , and d_{n-1} dividing d_n ensures that the diagonal matrix \mathbf{d} is unique.

I use this precise Theorem 2.1 as a key tool for an apparently completely unrelated problem in my paper [1]. This problem is the construction of functions f on the cyclic group $\mathbb{Z}/d\mathbb{Z}$ of odd order whose convolution square is proportional to their square. Indeed the construction relies on an auxiliary abelian variety endowed with a unitary \mathbb{Q} -endomorphism ν , the symplectic form ω shows up as a polarization of the abelian variety, and the rational symplectic matrix g shows up as the “holonomy” of ν .

The first reference to Theorem 2.1 that I know is Shimura’s paper [15, Prop. 1.6]. Moreover in [16], Shimura points out the relevance of this theorem to show the commutativity of a Hecke algebra and hence to better understand the modular forms on Siegel upper halfspace. This theorem is also in [9, p.232] and is also used by Clozel, Oh and Ullmo in [8, p.23].

As we have seen, there is a version of Theorem 2.1 for the linear group $\mathrm{SL}(n, \mathbb{Q})$, see for instance Proposition 5.1. More generally, there is also a version of Theorem 2.1 for any simply-connected split semisimple algebraic group \mathbf{G} defined over \mathbb{Q} , if one chooses suitably the \mathbb{Z} -form, see Section 7.

3 The symplectic group over local fields

Before going on I would like to emphasize the analogy of this theorem with two classical theorems. These two classical theorems are valid for all algebraic semisimple groups G and are due respectively to E. Cartan and to F. Bruhat and J. Tits. I will not quote here their general formulation that can be found respectively in [12] and in [5] but only the special case where G is the symplectic group.

The first theorem is a decomposition theorem over the real field \mathbb{R} due to E. Cartan which is called either the “polar decomposition” or the “Cartan decomposition”. We set

$$\begin{aligned} \mathrm{SO}(2n) &:= \{g \in \mathrm{GL}(2n, \mathbb{R}) \mid {}^t g g = \mathbf{1}_{2n}\} \text{ and} \\ \mathrm{Sp}(n) &:= \mathrm{Sp}(n, \mathbb{R}) \cap \mathrm{SO}(2n). \end{aligned}$$

Note that the group $\mathrm{Sp}(n)$ is a maximal compact subgroup of the group $\mathrm{Sp}(n, \mathbb{R})$.

Theorem 3.1. (Cartan) *Let $g \in \mathrm{Sp}(n, \mathbb{R})$. Then there exist two matrices σ and σ' in $\mathrm{Sp}(n)$ and a positive real diagonal matrix $\mathbf{d} = \mathrm{diag}(d_1, \dots, d_n)$ with $d_1 \leq d_2 \leq \dots \leq d_n \leq 1$ such that*

$$g = \sigma \begin{pmatrix} \mathbf{d} & \mathbf{0} \\ \mathbf{0} & \mathbf{d}^{-1} \end{pmatrix} \sigma'.$$

The second theorem is a decomposition theorem over a local non archimedean field k due to F. Bruhat and J. Tits. We denote by \mathcal{O}_k the ring of integers of k and choose a uniformizer π in k , i.e. a generator of the maximal ideal of \mathcal{O}_k .

Note again that the group $\mathrm{Sp}(n, \mathcal{O}_k)$ is a maximal compact subgroup of the group $\mathrm{Sp}(n, k)$.

Theorem 3.2. (Bruhat, Tits) *Let $g \in \mathrm{Sp}(n, k)$. Then there exist two matrices σ and σ' in $\mathrm{Sp}(n, \mathcal{O}_k)$ and a diagonal matrix $\mathbf{d} = \mathrm{diag}(\pi^{p_1}, \dots, \pi^{p_n})$ with $p_1 \geq p_2 \geq \dots \geq p_n \geq 0$ integers such that*

$$g = \sigma \begin{pmatrix} \mathbf{d} & \mathbf{0} \\ \mathbf{0} & \mathbf{d}^{-1} \end{pmatrix} \sigma'.$$

The analogy between these three theorems is striking. It extends the analogy between the Smith normal form of an integral matrix and the singular value decomposition of a real matrix.

In this analogy *the group of integers points of a group defined over the rational* should be handled as *the maximal compact subgroup of a group defined over the real*. This rough analogy is an equality when dealing with non archimedean local field. Indeed, when k is a non-archimedean local field, the group of integer points is an open compact subgroup.

4 Bruhat-Tits buildings

F. Bruhat and J. Tits have described the analog of the Cartan decomposition for semisimple groups over non-archimedean local fields, in [4], [5], [6] and [7], by introducing new geometric spaces that are nowadays called Bruhat-Tits buildings and that extend the space of p -adic norms studied by Goldman and Iwahori in [10].

As explained in the book [13], these Bruhat-Tits buildings are very useful.

One of the reason is that they are $K(\pi, 1)$ -spaces for the lattices in semisimple p -adic groups.

Another reason is that they played the role of a model to follow in order to understand other finitely generated groups, like Coxeter groups, Artin groups, Baumslag-Solitar groups or Mapping class groups.

The relevance of the Bruhat-Tits buildings became even clearer to me when I used them with Hee Oh to prove a general polar decomposition for p -adic symmetric spaces in [2]. This polar decomposition was a key ingredient in our proof of equidistribution of S -integral points on rational symmetric spaces in [3].

5 The symplectic adapted basis

In this section we come back to elementary consideration and we discuss the structure of the *rational symplectic group* $\mathrm{Sp}(n, \mathbb{Q})$, and its relation with the *integral symplectic group* $\mathrm{Sp}(n, \mathbb{Z})$.

We first recall the well-known undergraduate “adapted basis theorem” for \mathbb{Z} -module or, equivalently, the “Smith normal form” for integral matrices. We denote by $\mathcal{M}(n, \mathbb{Z})$ the ring of $n \times n$ integral matrices.

Proposition 5.1. (Smith) *Let $g \in \mathcal{M}(n, \mathbb{Z})$. Then there exist σ and σ' in $\mathrm{SL}(n, \mathbb{Z})$ and an integral diagonal matrix $\mathbf{a} = \mathrm{diag}(a_1, \dots, a_n)$ with $a_1 | a_2 | \dots | a_n$, and such that*

$$g = \sigma \mathbf{a} \sigma'.$$

Theorem 2.1 follows from the following proposition which is a variation of the “adapted basis theorem” which takes into account the existence of a symplectic form. We introduce the set $\mathcal{Mp}(n, \mathbb{Z})$ of nonzero integral matrices which are proportional to elements of $\mathrm{Sp}(n, \mathbb{R})$,

$$\mathcal{Mp}(n, \mathbb{Z}) := \{g \in \mathcal{M}(2n, \mathbb{Z}) \mid {}^t g J g = \lambda^2 J \text{ for some } \lambda \text{ in } \mathbb{R}^*\}.$$

Proposition 5.2. *Let $g \in \mathcal{Mp}(n, \mathbb{Z})$. Then there exist two matrices σ and σ' in $\mathrm{Sp}(n, \mathbb{Z})$ and a positive integral diagonal matrix $\mathbf{a} = \mathrm{diag}(a_1, \dots, a_{2n})$ with $a_1 | a_2 | \dots | a_n$, with $a_n | a_{2n}$ and such that*

$$g = \sigma \mathbf{a} \sigma'.$$

Note that the matrix \mathbf{a} is also in $\mathcal{M}p(n, \mathbb{Z})$ and hence the products $a_j a_{n+j}$ do not depend on the positive integer $j \leq n$. Indeed it is equal to λ^2 . In particular, one has $a_{2n} | a_{2n-1} | \dots | a_{n+1}$.

For the proof of Proposition 5.2, we need the following lemma. We recall that a nonzero vector v of \mathbb{Z}^k is primitive if it spans the \mathbb{Z} -module $\mathbb{R}v \cap \mathbb{Z}^k$.

Lemma 5.3. *The group $\mathrm{Sp}(n, \mathbb{Z})$ acts transitively on the set of primitive vectors in \mathbb{Z}^{2n} .*

Denote by $e_1, \dots, e_n, f_1, \dots, f_n$ the canonical basis of \mathbb{Z}^{2n} so that our symplectic form is $\omega = e_1^* \wedge f_1^* + \dots + e_n^* \wedge f_n^*$.

Proof of Lemma 5.3. Let $v = (x_1, \dots, x_{2n})$ be a primitive vector in \mathbb{Z}^{2n} . We want to find $\sigma \in \mathrm{Sp}(n, \mathbb{Z})$ such that $\sigma v = e_1$.

This is true for $n = 1$. Using the subgroups $\mathrm{Sp}(1, \mathbb{Z})$ for the planes $\mathbb{Z}e_j \oplus \mathbb{Z}f_j$, with $j = 1, \dots, n$, we can assume that

$$x_{n+1} = \dots = x_{2n} = 0.$$

In this case the vector (x_1, \dots, x_n) is primitive in \mathbb{Z}^n .

Since $\mathrm{SL}(n, \mathbb{Z})$ acts transitively on the set of primitive vectors in \mathbb{Z}^n , we can find a block diagonal matrix $\sigma = \mathrm{diag}(\sigma_0, {}^t\sigma_0^{-1})$, with $\sigma_0 \in \mathrm{SL}(n, \mathbb{Z})$ such that $\sigma v = e_1$. This matrix σ belongs to $\mathrm{Sp}(n, \mathbb{Z})$. \square

Proof of Proposition 5.2. Set $\Gamma := \mathrm{Sp}(n, \mathbb{Z})$. The proof is by induction on n . It relies on a succession of steps, in the spirit of the Smith normal form, in which one multiplies on the right or on the left the matrix g by an “elementary” matrix to obtain a simpler matrix $g' \in \Gamma g \Gamma$. We have to pay attention that at each step the elementary matrix is symplectic.

We can assume that the gcd of the coefficients of g is equal to 1. We denote by λ the positive real factor such that g/λ belongs to $\mathrm{Sp}(n, \mathbb{R})$. Note that λ^2 is a positive integer. At the end of the proof we will see that $a_1 = 1$ and $a_{n+1} = \lambda^2$.

1st step: *We find $g' \in \Gamma g \Gamma$ such that $g'e_1 = e_1$.*

Since the coefficients of the integral matrix g are relatively prime, by Proposition 5.1, there exists a primitive vector v in \mathbb{Z}^{2n} such that gv is also primitive. According to lemma 5.3, there exists σ, σ' in Γ such that $\sigma gv = e_1$ and $\sigma'e_1 = v$. Then the matrix $g' := \sigma g \sigma'$ satisfies $g'e_1 = e_1$.

2nd step: We find $g' \in \Gamma g \Gamma$ with $g'e_1 = e_1$ and $\omega(g'e_j, f_1) = 0$ for $j > 1$.

By the first step, we can assume that

$$g = \begin{pmatrix} \alpha & \beta \\ \gamma & \delta \end{pmatrix} \text{ with } \alpha e_1 = e_1 \text{ and } \gamma e_1 = 0$$

In particular the first column of the integral matrix α is $(1, 0, \dots, 0)$. We would like the first row of α to be also of the form $(1, 0, \dots, 0)$. For that we choose $g' = g\sigma'$ where σ' is the symplectic transformation

$$\sigma' = \mathbf{1}_n + \sum_{1 < j \leq n} \alpha_{1,j} (f_j \otimes f_1^* - e_1 \otimes e_j^*) \in \text{Sp}(n, \mathbb{Z}),$$

where $\alpha_{1,j}$ are the coefficients of the first row of the matrix α .

3rd step: We find $g' \in \Gamma g \Gamma$ such that $g'e_1 = e_1$ and $g'f_1 = \lambda^2 f_1$.

By the second step, we can assume, writing $g = \begin{pmatrix} \alpha & \beta \\ \gamma & \delta \end{pmatrix}$ that both the first row and first column of α are $(1, 0, \dots, 0)$, and the first column of γ is $(0, \dots, 0)$. We would also like the first row of β to be $(0, \dots, 0)$. For that we choose $g' = g\sigma'$ where σ' is the symplectic transformation

$$\sigma' = \mathbf{1}_n - \beta_{1,1} e_1 \otimes f_1^* - \sum_{1 < j \leq n} \beta_{1,j} (e_j \otimes f_1^* + e_1 \otimes f_j^*) \in \text{Sp}(n, \mathbb{Z}).$$

Now by construction one has

$$\begin{aligned} \omega(g'e_j, f_1) &= 0 \quad \text{for } j < n, \\ \omega(g'e_1, f_1) &= 1 \quad \text{and} \\ \omega(g'f_j, f_1) &= 0 \quad \text{for } j \leq n. \end{aligned}$$

Since g'/λ is symplectic, this implies that $g'^{-1}f_1 = \lambda^{-2}f_1$, or equivalently, $g'f_1 = \lambda^2 f_1$ as required.

4th step: *Conclusion.*

By the third step, we can assume that $ge_1 = e_1$ and $gf_1 = \lambda^2 f_1$. Therefore g preserves the symplectic \mathbb{Z} -submodule of \mathbb{Z}^{2n} orthogonal of $\mathbb{Z}e_1 \oplus \mathbb{Z}f_1$, which admits $e_2, \dots, e_n, f_2, \dots, f_n$ as \mathbb{Z} -basis. We conclude by applying the induction hypothesis to the restriction $g' \in \mathcal{M}p(n-1, \mathbb{Z})$ of g to this \mathbb{Z} -module. \square

6 The strong approximation theorem

In this section, we give a non elementary proof of the decomposition theorem 2.1 for $\mathrm{Sp}(n, \mathbb{Q})$. We will deduce this theorem from the Bruhat-Tits decomposition theorem 3.2 for $\mathrm{Sp}(n, \mathbb{Q}_p)$ thanks to the strong approximation theorem.

First, I recall the strong approximation theorem. I will not quote here the general formulation for a simply-connected isotropic \mathbb{Q} -simple algebraic group defined over \mathbb{Q} that can be found in [14] but only the special case where G is the symplectic group.

For $p = 2, 3, 5, \dots$ a prime number, we denote by \mathbb{Q}_p the p -adic local field and by \mathbb{Z}_p its ring of integers.

We denote by $\widehat{\mathbb{Q}} = \prod'_p \mathbb{Q}_p$ the locally compact ring of finite adèles which is the restricted product of the \mathbb{Q}_p with respect to the open subrings \mathbb{Z}_p . The product $\widehat{\mathbb{Z}} := \prod_p \mathbb{Z}_p$ is then a maximal compact open subring of $\widehat{\mathbb{Q}}$.

Note that, thanks to the diagonal embedding, \mathbb{Q} is a dense subring in $\widehat{\mathbb{Q}}$. This means that $\widehat{\mathbb{Q}} = \mathbb{Q} + \widehat{\mathbb{Z}}$ and that \mathbb{Z} is dense in $\widehat{\mathbb{Z}}$.

By construction the symplectic group $\mathrm{Sp}(n, \widehat{\mathbb{Q}})$ is a locally compact group that contains $\mathrm{Sp}(n, \widehat{\mathbb{Z}})$ as a maximal compact open subgroup. It also contains the group $\mathrm{Sp}(n, \mathbb{Q})$.

Here is the strong approximation theorem for the symplectic group.

Theorem 6.1. *The group $\mathrm{Sp}(n, \mathbb{Q})$ is dense in $\mathrm{Sp}(n, \widehat{\mathbb{Q}})$.*

This means that,

$$\mathrm{Sp}(n, \widehat{\mathbb{Q}}) = \mathrm{Sp}(n, \mathbb{Q})\mathrm{Sp}(n, \widehat{\mathbb{Z}})$$

and that

$$\mathrm{Sp}(n, \mathbb{Z}) \text{ is dense in } \mathrm{Sp}(n, \widehat{\mathbb{Z}}).$$

If we collect together the Bruhat-Tits decomposition in Theorem 3.2 for all p -adic fields $k = \mathbb{Q}_p$, one gets

Theorem 6.2. *Let $g \in \mathrm{Sp}(n, \widehat{\mathbb{Q}})$. Then there exist two matrices σ and σ' in $\mathrm{Sp}(n, \widehat{\mathbb{Z}})$ and a positive integral diagonal matrix $\mathbf{d} = \mathrm{diag}(d_1, \dots, d_n)$ with*

$d_1|d_2|\dots|d_n$ such that

$$g = \sigma \begin{pmatrix} \mathbf{d} & \mathbf{0} \\ \mathbf{0} & \mathbf{d}^{-1} \end{pmatrix} \sigma'.$$

We can now give the non-elementary proof of the symplectic Smith normal form.

Proof of Theorem 2.1. Let $g \in \mathrm{Sp}(n, \mathbb{Q})$.

According to the combined Bruhat-Tits decomposition theorem 6.2, one can write

$$g = \sigma \mathbf{a} \sigma'$$

with σ, σ' in $\mathrm{Sp}(n, \widehat{\mathbb{Z}})$ and with $\mathbf{a} = \begin{pmatrix} \mathbf{d} & \mathbf{0} \\ \mathbf{0} & \mathbf{d}^{-1} \end{pmatrix}$ where $\mathbf{d} = \mathrm{diag}(d_1, \dots, d_n)$ is a positive integral diagonal matrix with $d_1|d_2|\dots|d_n$.

According to the strong approximation theorem 6.1, one can write

$$\sigma = \sigma_0 \eta$$

with σ_0 in $\mathrm{Sp}(n, \mathbb{Z})$ and with η in an arbitrarily small neighborhood of $\mathbf{1}$ in $\mathrm{Sp}(n, \widehat{\mathbb{Z}})$. More precisely we choose η such that the element $\sigma'_0 := \mathbf{a}^{-1} \eta \mathbf{a} \sigma'$ belongs to $\mathrm{Sp}(n, \widehat{\mathbb{Z}})$. Then one has the equality

$$g = \sigma_0 \mathbf{a} \sigma'_0$$

where both σ_0 and $\sigma'_0 = \mathbf{a}^{-1} \sigma_0^{-1} g$ belong to $\mathrm{Sp}(n, \mathbb{Z})$. □

7 Chevalley groups

Let \mathbf{G} be a simply-connected Chevalley group. See [17] for a concrete presentation of the group $\mathbf{G}(\mathbb{Z})$, and see [11] for other nice examples of \mathbb{Z} -models of simple algebraic groups over \mathbb{Q} . This \mathbf{G} is a reductive scheme-group over \mathbb{Z} such that as a \mathbb{Q} -group \mathbf{G} is a \mathbb{Q} -split simply connected quasi-simple algebraic group. By construction, this algebraic group contains a \mathbb{Q} -split maximal torus \mathbf{A} such that the group of integral points $\mathbf{N}(\mathbb{Z})$ of the normalizer of \mathbf{A} surjects onto the Weyl group of $(\mathbf{A}(\mathbb{C}), \mathbf{G}(\mathbb{C}))$.

Since \mathbf{G} is simply connected and \mathbb{R} -isotropic, by strong approximation, the group $\mathbf{G}(\mathbb{Q})$ is dense in $\mathbf{G}(\widehat{\mathbb{Q}})$. On the other hand, for all prime integer p , one can consider the simply connected simple p -adic Lie group $G := \mathbf{G}(\mathbb{Q}_p)$,

its split maximal torus $A := \mathbf{A}(\mathbb{Q}_p)$ and its normalizer $N := \mathbf{N}(\mathbb{Q}_p)$. The maximal compact subgroup $K := \mathbf{G}(\mathbb{Z}_p)$ is a good compact subgroup in the sense that one has the equality $N = (N \cap K)A$. Hence, according to Bruhat-Tits, one has the decomposition $\mathbf{G}(\mathbb{Q}_p) = \mathbf{G}(\mathbb{Z}_p)\mathbf{A}(\mathbb{Q}_p)\mathbf{G}(\mathbb{Z}_p)$.

Therefore the same proof as in Chapter 6 gives the following theorem due to Steinberg in [17, Theorem 21]

Theorem 7.1. *Let \mathbf{G} be a simply connected Chevalley group and $g \in \mathbf{G}(\mathbb{Q})$. Then there exist two elements σ and σ' in $\mathbf{G}(\mathbb{Z})$ and an element \mathbf{a} in $\mathbf{A}(\mathbb{Q})$ such that*

$$g = \sigma \mathbf{a} \sigma'.$$

Remark. Such a decomposition is not true when we replace \mathbb{Q} by a number field \mathbb{K} whose ring of integer \mathcal{O} is not principal. Here is an example with

$$\mathbf{G}(\mathbb{K}) := \mathrm{SL}(2, \mathbb{K}), \quad \mathbf{G}(\mathcal{O}) := \mathrm{SL}(2, \mathcal{O}),$$

$$\mathbf{A}(\mathbb{K}) := \left\{ \mathbf{a} = \begin{pmatrix} \mathbf{d} & \mathbf{0} \\ \mathbf{0} & \mathbf{d}^{-1} \end{pmatrix} \mid \mathbf{d} \in K^* \right\}.$$

In this case the product $\mathbf{G}(\mathcal{O}) \mathbf{A}(\mathbb{K}) \mathbf{G}(\mathcal{O})$ is not equal to $\mathbf{G}(\mathbb{K})$. For instance, when $K = \mathbb{Q}[i\sqrt{5}]$ and $\mathcal{O} = \mathbb{Z}[i\sqrt{5}]$, this product does not contain the matrix

$$g = \begin{pmatrix} (1-i\sqrt{5})/2 & i\sqrt{5} \\ -1 & 2 \end{pmatrix}.$$

Indeed the element $\mathbf{d} \in K^*$ should be a unit in all completion $K_{\mathfrak{p}}$ except for the prime ideal $\mathfrak{p}_0 = 2\mathbb{Z} \oplus (1+i\sqrt{5})\mathbb{Z}$ in which case it should be a uniformizer. Such an element \mathbf{d} would be a generator of the ideal \mathfrak{p}_0 . This is a contradiction, since this ideal \mathfrak{p}_0 is not principal.

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