$\mathbb{A}^1$-INVARIANCE FOR UNSTABLE K_2

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1. AIM OF THE PAPER

The aim of this text is to prove that the non-stable K_2-functors K_2^G, where G is a simply connected Chevalley group of suitable type, satisfy $\mathbb{A}^1$-invariance on regular rings R containing a field k, that is,

(1.1)
$$K_2^G(R[t]) = K_2^G(R).$$

As a corollary, we should easily deduce that

$$K_2^G(R) = KV_2^G(R),$$

where $KV_2^G(R)$ is the Karoubi–Villamayor K-functor associated to G. This functor originates from [5]. The above equality by e.g. [2, Corollary 4.3.3] implies that $\pi_1^{\mathbb{A}^1}(G)(R) = K_2^G(R)$, i.e. we obtain an explicit presentation for the $\mathbb{A}^1$-fundamental group of G in the sense of Morel–Voevodsky.

"Suitable type" here means that we consider only the cases where we know the centrality of K_2, or at least the Quillen-Suslin lgp. Some intermediate steps can be proved in larger generality.

Essentially, we need to prove that $K_2^G(k[x_1, \ldots, x_n]) = K_2^G(k)$. (Then (1.1) follows by standard geometric methods.) There are two models: Tulenbaev's proof for the SL_n case [11] and Stavrova's proof for K_1^G [9]. Tulenbaev [11] uses stabilization of the K_2-functor, and the good properties of the limit=algebraic K-theory. In [9] stabilization is not used. However, the key steps of both proofs are the same: the case of $R = k$ (hidden somewhere around [11, p. 140], or, respectively, [9, Theorem 3.1]); Quillen-Suslin lgp; $\mathbb{P}^1$-gluing (see [11, Theorem 5.1] or [9, Theorem 1.1]).

1.1. **The case $R = k$.** We consider the case of $K_2^G(k[t])$ vs. $K_2^G(k)$. (As in the $\mathbb{A}^1$-invariance of K_1^G, this case should be used to deduce that $K_2^G(k[t_1, \ldots, t_n]) = K_2^G(k)$.)

In Tulenbaev's framework, it follows from stabilization. However, the equality $K_2^G(k[t]) = K_2^G(k)$ is sort of known for all groups. Namely, in [14, Theorem 5.1]: let k be an infinite field and let G be a connected reductive group over k. Then the inclusion $k \hookrightarrow k[t]$ induces an isomorphism

$$H_\bullet(G(k), \mathbb{Z}) \xrightarrow{\cong} H_\bullet(G(k[t]), \mathbb{Z}),$$

if the order of the fundamental group of G is invertible in k. Once we know that the homology H_2 coincides with K_2^G (on both sides), this gives the result. It would be nice to check Wendt's proof; maybe, discuss it in a seminar?

Is it necessary to know the centrality in order to show that K_2^G coincides with H_2? If yes, then we probably know it for $K_2^G(k)$ even for isotropic groups [3], but only for the

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good Chevalley groups for $K_2^G(k[t])$. We should try to understand what is proved in [12, Proposition 5.3] using only the universality of the Steinberg group. This may be useful. The paper is unpublished, so again everything should be double-checked if you want to refer to it.

1.2. Plan of the proof.

plan:3t
(1) (**done**, see Theorem 2). Let R be a local ring. Show that
$$\text{St}^G(R[t^{\pm 1}]) = i_+(\text{St}^G(R[t]))i_-(\text{St}^G(R[t^{-1}]))i_+(\text{St}^G(R[t]))$$
Here $i_\pm$ denote the natural homomorphisms into $\text{St}^G(R[t^{\pm 1}])$.

plan:k[t]
(2) (**done**, see Theorem 4). Show that $K_2^G(k[t]) = K_2^G(k)$.

:k-intersect
(3) (**done**). Consequently, $\text{St}^G(k[t]) \to \text{St}^G(k[t^{\pm 1}])$ is injective and $\text{St}^G(k[t]) \cap \text{St}^G(k[t^{-1}]) = \text{St}^G(k)$ inside $\text{St}^G(k[t^{\pm 1}])$. Also, $K_2^G(k) = K_2^G(k[t^{\pm 1}])$.
The first claim uses (2). The second claim follows from (2) and (1).

plan:QSlgp
plan:Zglu
(4) (**done** for split ACDE, see Theorem 1.(ii)). Prove Quillen-Suslin lgp for K_2^G.

(5) (Zariski gluing) for any commutative ring A and any non-nilpotent $f, g \in A$ such that $A = fA + gA$, the sequence of pointed sets
$$1 \longrightarrow K_2^G(A) \xrightarrow{g \mapsto (g,g)} K_2^G(A_f) \times K_2^G(A_g) \xrightarrow{(g_1, g_2) \mapsto g_1 g_2^{-1}} K_2^G(A_{fg})$$
is exact. The proof is usually almost the same as for (4).
(Remark. It seems that we need this property only for $A = R[t]$ and f, g non-constant polynomials.)

plan:S-lemma
(6) (S-lemma) Let A be a commutative ring, S a multiplicative subset of A. If
$$K_2^G(A[X_1, \ldots, X_n]) = K_2^G(A)$$
for some $n \geq 1$, then $K_2^G(A_S[X_1, \ldots, X_n]) = K_2^G(A_S)$ as well.
This should be easy; see [1, Lemma 3.6].

plan:Nglu
(7) (Nisnevich gluing) Assume that B is a subring of a commutative ring A, and let $h \in B$ be a non-nilpotent element. Denote by $F_h : A \to A_h$ the localization homomorphism.
(i) If $Ah + B = A$, i.e. the natural map $B \to A/Ah$ is surjective, then for any $x \in \text{St}^G(A_h)$ there exist $y \in \text{St}^G(A)$ and $z \in \text{St}^G(B_h)$ such that $x = F_h(y)z$.
(ii) If moreover $Ah \cap B = Bh$, i.e. $B/Bh \to A/Ah$ is an isomorphism, and h is not a zero divisor in A, then the sequence of pointed sets
$$K_2^G(B) \xrightarrow{g \mapsto (F_h(g), g)} K_2^G(B_h) \times K_2^G(A) \xrightarrow{(g_1, g_2) \mapsto g_1 F_h(g_2)^{-1}} K_2^G(A_h)$$
is exact.
This should use something from the proof of (4) or (5); see [9, Lemma 3.4].

plan:P1
(8) ($\mathbb{P}^1$-gluing) Let A be any commutative ring. Show that the sequence of pointed sets
$$1 \longrightarrow K_2^G(A) \xrightarrow{g \mapsto (g,g)} K_2^G(A[t]) \times K_2^G(A[t^{-1}]) \xrightarrow{(g_1, g_2) \mapsto g_1 g_2^{-1}} K_2^G(A[t, t^{-1}])$$
is exact.
This should use (1)–(4).
(a) Prove Proposition 4.6. This is hard. Have no idea how this can be proved at the moment.
(b) Prove $\mathbb{P}^1$-glueing using all the above facts.

<div style="margin-left: 2em">

`plan:[]f`

(9) (Main corollary of $\mathbb{P}^1$-gluing) Let A be any commutative ring, and let $f \in A[t]$ be a monic polynomial. Show that $K_2^G(A[t]) \to K_2^G(A[t]_f)$ is injective.

    The proof uses (5) and (8).

`plan:k(t)`

(10) Prove that $K_2^G(k(t)) = K_2^G(k)$. This may be a bit tricky; I will think if we can get rid of it. I don't think Tulenbaev uses it. Unsure whether this is true (?). This is true for SK_1 but in view of Milnor's theorem can not hold for K_1 and K_2.

`plan:k[tn]`

(11) Prove that

$$K_2^G(k[t_1, \ldots, t_n]) = K_2^G(k).$$

    If we strictly follow the pattern of K_1^G, this uses (9), (2), and (10). There may be other ways.

`plan:final`

(12) Final result: let R be a regular ring containing a field k. Then $K_2^G(R[t]) = K_2^G(R)$. This uses (4), (11) and (7).

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2. Steinberg groups of Chevalley groups: preliminaries

2.1. **Definition and basic properties.** Let G be a split simple Chevalley groups with a root system Φ of rank ≥ 2. Recall that the *Steinberg group* $\mathrm{St}^G(R)$ (also denoted $\mathrm{St}(\Phi, R)$) is defined by means of generators $\mathcal{X}_{\Phi,R} = \{x_\alpha(\xi) \mid \xi \in R, \alpha \in \Phi\}$ and the set of relations $\mathcal{R}_{\Phi,R}$ defined as follows:

`{rel:add}`

(2.1)
$$x_\alpha(s)x_\alpha(t) = x_\alpha(s + t),$$

`{rel:CCF}`

(2.2)
$$[x_\alpha(s), x_\beta(t)] = \prod x_{i\alpha+j\beta}\left(N_{\alpha\beta ij}\, s^i t^j\right), \quad \alpha \neq -\beta, \quad N_{\alpha\beta ij} \in \mathbb{Z}.$$

The indices i, j appearing in the right-hand side of the above relation range over all positive natural numbers such that $i\alpha + j\beta \in \Phi$. The structure constants $N_{\alpha\beta ij} = \pm 1, 2, 3$ appearing in (2.2) depend only on Φ and can be computed precisely.

    Recall that for $\alpha \in \Phi$, $\varepsilon \in R^*$ the semisimple root elements $h_\alpha(\varepsilon)$ are defined as $h_\alpha(\varepsilon) = w_\alpha(\varepsilon)w_\alpha(-1)$. Denote by $\mathrm{W}(\Phi, R)$ the subgroup of $\mathrm{St}(\Phi, R)$ generated by all elements $w_\alpha(\varepsilon)$, $\varepsilon \in R^*$.

2.2. **Tulenbaev's lifting property and its corollaries.** Throughout this section $I \trianglelefteq A$ is an ideal of arbitrary commutative ring A. For a nonnilpotent element $a \in A$ denote by $\lambda_a \colon A \to A_a$ the morphism of principal localization at a. Consider the following commutative square.

`{msq}`

(2.3)

$$\begin{array}{ccc} A & \xrightarrow{\lambda_a} & A_a \\ \downarrow & & \downarrow \\ A/I & \xrightarrow{\overline{\lambda_a}} & A_a/I_a \end{array}$$

Notice that (2.3) is a pull-back square if and only if λ_a induces an isomorphism of I and I_a. Such squares are usually called *Milnor squares* in the literature, see [13, Ch. I, § 2].

    The following property of linear Steinberg groups was discovered for the first time by Tulenbaev (see [11, Lemmas 2.3, 3.2]) and plays a key role in the sequel.

`def:tlp` **Definition 2.1.** We say that the Steinberg group functor St^G satisfies *Tulenbaev's lifting property* if for every pull-back square (2.3) the following lifting problem has a solution.

$$
\begin{array}{ccc}
\mathrm{St}^G(A, I) & \xrightarrow{\mu} & \mathrm{St}^G(A) \\
\downarrow & \nearrow & \downarrow{\lambda_a^*} \\
\mathrm{St}^G(A_a, I) & \xrightarrow{\mu} & \mathrm{St}^G(A_a)
\end{array}
$$

Theorem 1. *Assume that G satisfies Tulenbaev property* (2.1) *then the following facts are true for arbitrary commutative ring A:*

`thm:dp` *(i) A dilation principle holds for $\mathrm{St}^G(-)$, i. e. if $g \in \mathrm{St}^G(A[t], tA[t])$ is such that equality $\lambda_a^*(h) = 1$ holds in $\mathrm{St}^G(\Phi, R_a[t])$ then for sufficiently large n one has*

$$ ev^*_{\left[\frac{R[t] \to R[t]}{t \mapsto a^n \cdot t}\right]}(h) = 1. $$

`thm:lg-k2` *(ii) A local-global principle holds for $\mathrm{St}^G(-)$, i. e. an element $g \in \mathrm{St}^G(A[t], tA[t])$ is trivial if and only if its image in $\mathrm{St}^G(A_m[t], tA_m[t])$ is trivial for all maximal ideals $m \unlhd A$.*

`thm:centr` *(iii) $K_2^G(A)$ is contained in the centre of $\mathrm{St}^G(A)$.*

Proof. Follows by the same argument as [11, Theorem 2.1] or [8, Theorem 2] $\qquad\square$

2.3. **The action of torus.** Throughout this subsection $G = G_{\mathrm{ad}}$ denotes a split simple Chevalley group of adjoint type with the root system Φ of rank ≥ 2. Denote by $T = T_{\mathrm{ad}}$ the torus of G and by $T(R)$ its group of R-points.

We identify the root lattice $X^*(T) = \mathrm{Hom}(T, \mathbf{G}_m)$ with the lattice $\mathbb{Z}\,\Phi$ in the obvious way. In particular, for $\alpha \in \Phi$ we denote by α_R the corresponding map $T(R) \to R^*$ on R-points. An element $h \in T(R)$ defines a permutation of the set $\mathcal{X}_{\Phi,R}$ of generators of $\mathrm{St}^G(R)$ as follows:

$$ (2.4) \qquad\qquad h \cdot x_\alpha(\xi) = x_\alpha(\alpha_R(h) \cdot \xi). $$

Notice that h preserves the defining relations $\mathcal{R}_{\Phi,R}$ of the Steinberg group (and thus, determines a permutation of $\mathcal{R}_{\Phi,R}$). Indeed, the assertion is immediate for relation (2.1). Verification of the fact that h preserves (2.2) is a routine computation which should use the fact that for $\alpha, \beta \in \mathbb{Z}\,\Phi$ one has $(\alpha + \beta)_R(h) = \alpha_R(h) \cdot \beta_R(h)$.

3. DECOMPOSITION THEOREMS FOR $\mathrm{St}^G(A[t^{\pm 1}])$ AND $\mathrm{St}^G(A((t)))$.

Lemma 3.1. *Let (R, m) be a local ring, and let G be a simply connected simple group over R of isotropic rank ≥ 2. Let $i_+ : \mathrm{St}^G(R[t]) \to \mathrm{St}^G(R[t^{\pm 1}])$ and $i_- : \mathrm{St}^G(R[t^{-1}] \to \mathrm{St}^G(R[t^{\pm 1}])$ be the natural homomorphisms. Then*

$$ i_+\left(\mathrm{St}^G(m \cdot R[t])^{\mathrm{St}^G(R[t])}\right) i_-\left(\mathrm{St}^G(R[t^{-1}]\right) = i_-\left(\mathrm{St}^G(R[t^{-1}]\right) i_+\left(\mathrm{St}^G(m \cdot R[t])^{\mathrm{St}^G(R[t])}\right) $$

inside $\mathrm{St}^G(R[t^{\pm 1}])$.

Proof. This is proved exactly as [9, Lemma 5.12]. $\qquad\square$

`thm:3t` **Theorem 2.** *Let R be a local ring, and let G be a simply connected simple group over R of isotropic rank ≥ 2. Let $i_+ : \mathrm{St}^G(R[t]) \to \mathrm{St}^G(R[t^{\pm 1}])$ and $i_- : \mathrm{St}^G(R[t^{-1}] \to \mathrm{St}^G(R[t^{\pm 1}])$ be the natural homomorphisms. Then*

$$ \mathrm{St}^G(R[t^{\pm 1}]) = i_+(\mathrm{St}^G(R[t]))i_-(\mathrm{St}^G(R[t^{-1}]))i_+(\mathrm{St}^G(R[t])). $$

Proof. This is proved exactly as [9, Theorem 5.1]. □

4. $\mathbb{P}^1$-GLUING

Throughout this section $G = G(\Phi, -)$ denotes an arbitrary Chevalley group scheme of type Φ. We also assume everywhere below that Φ is irreducible and has rank ≥ 2.

`def:p1g` **Definition 4.1.** Let F be a group-valued functor from **CRings** to **Groups** and let A be a commutative ring. Consider the following commutative diagram of rings.

$$
\begin{array}{ccc}
A & \xrightarrow{\ i_+\ } & A[t] \\
{\scriptstyle i_-}\downarrow & & \downarrow{\scriptstyle j_+} \\
A[t^{-1}] & \xrightarrow{\ j_-\ } & A[t, t^{-1}]
\end{array}
$$

We say that F satisfies the $\mathbb{P}^1$-*glueing property for* A if the following sequence of groups is exact in the middle term:

$$ F(A) \xhookrightarrow{\ \Delta_A\ } F(A[t]) \times F(A[t^{-1}]) \xrightarrow{\ \pm_A\ } F(A[t, t^{-1}]). $$

Here Δ_A denotes the (split injective) diagonal map $F(i_+, i_-)$ and $\pm_A$ is a shorthand for $m \circ (F(j_+)\pi_1, inv \circ F(j_-)\pi_2)$ where m and inv denote the morphisms of inversion and multiplication in the group $F(A[t, t^{-1}])$.

The main result of this section is the following theorem which plays a crucial role in the sequel.

`thm:p1` **Theorem 3.** *The Steinberg group functor* $\mathrm{St}^G(-)$ *satisfies* $\mathbb{P}^1$-*glueing property for an arbitrary commutative ring* A.

Proof. Let (g^+, g^-) be an element of $\mathrm{St}^G(A[t]) \times \mathrm{St}^G(A[t^{-1}])$ such that the equality $g^+ = g^-$ holds in $\mathrm{St}^G(A[t, t^{-1}])$.

Let M be a maximal ideal of A. By Proposition 4.8 below the functor $\mathrm{St}^G(-)$ satisfies $\mathbb{P}^1$-glueing property for the local ring A_M hence $(\lambda_M^*(g_+), \lambda_M^*(g_-)) = \Delta_{A_M}(\lambda_M^*(g^+)(0))$ and in the groups $\mathrm{St}^G(A_M[t])$ and $\mathrm{St}^G(A_M[t^{-1}])$ we have the equalities:

$$ \lambda_M^*(g^+ \cdot g^+(0)^{-1}) = \lambda_M^*(g^+) \cdot \lambda_M^*(g^+)(0)^{-1} = 1; \qquad \lambda_M^*(g^- \cdot g^+(0)^{-1}) = 1. $$

Now, by the local-global principle for $\mathrm{St}^G(-)$ (see Theorem 1.(ii)) these equalities hold globally and $(g^+, g^-) = \Delta_A(g^+(0))$, as claimed. □

Corollary 4.2. *Let A be any commutative ring and $f \in A[t]$ be a monic polynomial. Then the map $K_2^G(A[t]) \to K_2^G(A[t]_f)$ is injective.*

Proof. □

4.1. **The case of a field.** Throughout this section k denotes arbitrary field k.

`thm:k[t]`
`satz1` **Theorem 4.** *The following statements are true.*

(i) *For $A = k, k[t]$ the subgroup $K_2^G(A) \trianglelefteq \mathrm{St}^G(A)$ is generated by elements of the form*

$$ h_\alpha(uv)h_\alpha(u)^{-1}h_\alpha(v)^{-1}, \ u, v \in k^*. $$

(ii) *As a consequence, the canonical injection $K_2^G(k) \hookrightarrow K_2^G(k[t])$ is an isomorphism.*

Proof. See [7, Satz 1] and the corollary after it. $\square$

`cor:k[t]inj` **Corollary 4.3.** *Let G, k be as in the above theorem. Then the functor $\mathrm{St}^G(-)$ satisfies $\mathbb{P}^1$-glueing for k.*

Proof. Clearly, $g \in \mathrm{Ker}\,(\mathrm{St}^G(k[t]) \to \mathrm{St}^G(k[t^{\pm 1}]))$ implies $g \in K_2^G(k[t])$. Since $K_2^G(k[t]) = K_2^G(k)$, and there is a section $K_2^G(k[t^{\pm 1}]) \to K_2^G(k)$, the map is injective. Second claim: take $g \in \mathrm{St}^G(k[t]) \cap \mathrm{St}^G(k[t^{-1}])$. Then the image $\phi(g)$ belongs to $E(k) = E(k[t]) \cap E(k[t^{-1}])$, and after adjusting g by an element of $\mathrm{St}^G(k)$, we can assume that $g \in K_2^G(k[t]) \cap K_2^G(k[t^{-1}])$. Hence $g \in K_2^G(k) \subseteq \mathrm{St}^G(k)$. $\square$

Corollary 4.4. *Let G, k be as in Theorem 4. Then $K_2^G(k[t^{\pm 1}]) = K_2^G(k)$.*

Proof. We use Theorem 2. Take $g \in K_2^G(k[t^{\pm 1}])$, then $g = x_1 y x_2$, $x_i \in \mathrm{St}^G(k[t])$, $y \in \mathrm{St}^G(k[t^{-1}])$. Since $E(k[t]) \cap E(k[t^{-1}]) = E(k)$, we have $y \in \mathrm{St}^G(k) K_2^G(k[t^{-1}]) = \mathrm{St}^G(k)$ and $x_1 x_2 \in \mathrm{St}^G(k)$. That is, $g \in K_2^G(k)$. $\square$

4.2. **The case of a local ring.** For the rest of this section A denotes an arbitrary commutative local ring with the maximal ideal m and the residue field k. We denote by π the canonical projection $A \to k$. Throughout this section we will employ the following notation:

- R denotes the Laurent polynomial ring $A[t, t^{-1}]$;
- B denotes the subring $A[t] + m[t^{-1}]$ of R consisting of Laurent polynomials $f(t, t^{-1})$ whose coefficients of terms of negative degree belong to m;
- I denotes the ideal $m[t, t^{-1}]$ of R (which can be also considered as an ideal of B).

Consider the following commutative diagram of groups.

`{diag:cs}` (4.1)

$$
\begin{array}{ccccccc}
C_B & \longrightarrow & \mathrm{St}^G(B, I) & \xrightarrow{\mu^{+0}} & \mathrm{St}^G(B) & \xrightarrow{p^{+0}} & \mathrm{St}^G(k[t]) \\
\downarrow{\scriptstyle k^+} & & \downarrow{\scriptstyle j^+} & \overset{\varphi}{\nearrow} & \downarrow{\scriptstyle i^+} & & \downarrow{\scriptstyle \overline{i^+}} \\
C_R & \longrightarrow & \mathrm{St}^G(R, I) & \xrightarrow[\mu^{\pm}]{} & \mathrm{St}^G(R) & \xrightarrow[p^{\pm}]{} & \mathrm{St}^G(k[t, t^{-1}])
\end{array}
$$

Notice that by Corollary 4.3 the map $\overline{i^+}$ in the right-hand side of the above diagram is injective. Invoking Tulenbaev's property 2.1 we also find a lifting map in the central square of the diagram.

Our next result is analogous to [11, Lemma 3.1(e)] (cf. also with [4, § 2.3A]).

`cor:bruhat` **Lemma 4.5.** *The Steinberg group $\mathrm{St}^G(A)$ admits the following analogue of the Bruhat decomposition:*

$$\mathrm{St}^G(A) = \mathrm{U}(\Phi^+, A) \cdot \mathrm{W}(\Phi, A) \cdot \mathrm{U}(\Phi^+, A) \cdot \mathrm{Im}\,(\mathrm{St}^G(A, m) \to \mathrm{St}^G(A)).$$

Proof. First of all, notice that $\mathrm{St}^G(k)$ admits Bruhat decomposition for arbitrary field k:

$$\mathrm{St}^G(k) = \mathrm{U}(\Phi^+, k) \cdot \mathrm{W}(\Phi, k) \cdot \mathrm{U}(\Phi^+, k).$$

Indeed, this is an immediate consequence of the classical Bruhat decomposition for the linear groups (see e.g. [10, Theorem 4]) and the fact that $K_2^G(k)$ is central in $\mathrm{St}^G(k)$ and is generated by symbols $h_\alpha(u)$ lying in $\mathrm{W}(\Phi, k)$ (cf. Theorem 4.(i)).

Denote the map $A \to k$ by π. By ??? the first factor of the decomposition coincides with $\mathrm{Ker}\,(\pi_*)$ whereas by Lemma 4.5 the product of the last three factors is mapped epimorphically onto $\mathrm{St}^G(k)$. $\square$

The following result is analogous to [11, Proposition 4.1].

prop:kersurj **Proposition 4.6.** *The map k^+ is surjective.*

Proof. □

Using a simple diagram chasing argument we are able to obtain the following result.

cor:tulinj **Corollary 4.7.** *The canonical map $i^+\colon \mathrm{St}^{\mathrm{G}}(B) \to \mathrm{St}^{\mathrm{G}}(R)$ is injective.*

Proof. Let $g \in \mathrm{St}^{\mathrm{G}}(B^+)$ be an element of $\mathrm{Ker}\,(i^+)$. Since g also lies in $\mathrm{Ker}\,(p^{+0})$ it comes from some $\widetilde{g} \in \mathrm{St}^{\mathrm{G}}(B^+, I)$ via μ^{+0}. Now $j^+(\widetilde{g})$ lies in $C_\pm$, hence, by Proposition 4.6 it comes from some $\widehat{g} \in C_{+0}$ via k^+. Finally, $g = \varphi(j^+(\widetilde{g})) = \varphi(k^+(\widehat{g})) = \mu^{+0}(\widehat{g}) = 1$, as claimed. □

prop:p1g **Proposition 4.8** ($\mathbb{P}^1$-glueing in the local case). *Blah-blah-blah*

Proof. □

Appendices

A. Linear Steinberg group in rank 3

The main goal of this subsection is to show that Tulenbaev's [11, Lemma 2.3] remains valid for the linear Steinberg group of rank ≥ 3. In order to do this we will need yet another presentation for the relative linear Steinberg group (cf. [8, Definitions 3.3 and 3.7]).

Definition A.1. The relative Steinberg group $\mathrm{St}^*(n, R, I)$ is the group defined by the following two families generators and four families of relations.

- Generators:
  (1) $X^1(u, v)$, where $u \in \mathrm{E}(n, R) \cdot e_1$, $v \in I^n$ such that $v^t \cdot u = 0$;
  (2) $X^2(u, v)$, where $u \in I^n$, $v \in \mathrm{E}(n, R) \cdot e_1$ such that $v^t \cdot u = 0$.
  Notice that ϕ maps both $X^1(u, v)$ and $X^2(u, v)$ to $T(u, v) = e + u \cdot v^t \in \mathrm{E}(n, R, I)$.
- Relations:
  (1) $X^1(u, v) \cdot X^1(u, w) = X^1(u, v + w)$, $u \in \mathrm{E}(n, R) \cdot e_1$, $v, w \in I^n$;
  (2) $X^2(u, v) \cdot X^2(w, v) = X^2(u + w, v)$, $u, w \in I^n$, $v \in \mathrm{E}(n, R) \cdot e_1$;
  (3) $^{X^\sigma(u^2, v^2)}X^\tau(u^1, v^1) = X^\tau(T(u^2, v^2) \cdot u^1, T(v^2, u^2)^{-1} \cdot v^1)$, $\sigma, \tau = 1, 2$;
  (4) $X^1(g \cdot e_1, g^* \cdot be_2) = X^2(g \cdot be_1, g^* \cdot e_2)$ where $b \in I$ and $g^* = g^{t-1}$ denotes the contragradient matrix.

Lemma A.2. *The groups $\mathrm{St}^*(n, R, I)$ and $\mathrm{St}(n, R, I)$ are isomorphic.*

Proof. **TODO:** □

The next step of the proof is to is construct certain elements in $\mathrm{St}(n, R)$ similar to Tulenbaev's elements $X_{u,v}(a)$ see [11, § 1].

Let $v \in R^n$ be a column. Denote by $O(v)$ the submodule of R^n consisting of all columns w such that $w^t \cdot v = 0$. A column $w \in R^n$ is called v-*decomposable* if it can be presented as a finite sum $w = \sum_{i=1}^p w^i$ such that each w^i has at least two zero entries and $v^t \cdot w^i = 0$. Denote

by $D(v)$ the submodule of $O(v)$ consisting of all v-decomposable columns. For a column $v \in R^n$ denote by $I(v)$ the ideal of R spanned by its entries $v_1, \ldots, v_n$.

Let $u, v, w \in R^n$ be columns such that $w^t v = 0$. It is easy to check (cf. [6, Lemma 3.2]) that

$$(uv) \cdot w = \sum_{i<j} w_{ij}, \text{ where } w_{ij} = (w_i u_j - w_j u_i)(v_j e_i - v_i e_j) \in A^n.$$

The above decomposition is called the *canonical* decomposition of $(uv) \cdot w$. In particular, this shows that the column $a \cdot w$ is always v-decomposable for $a \in I(v)$, $w \in O(v)$, i.e. $I(v) \cdot O(v) \subseteq D(v)$. It is also straightforward to check that $D(v) \subseteq D(bv)$, $b \cdot D(v) \subseteq D(v)$ for $b \in R$.

Denote by B^1 the subset of $R^n \times R^n \times R$ consisting of triples (u, v, a) such that $v^t \cdot u = 0$, $v \in D(u)$, $a \in I(u)$. Denote by B^2 the set consisting of triples (v, u, a) such that $(u, v, a) \in B^1$.

lem:Zfacts

Lemma A.3. *Assume that $n \geq 4$. One can define two families of elements $Z^\tau(u, v, a)$, $\tau = 1, 2$ of the group $\mathrm{St}(n, R)$ parametrized by $(u, v, a) \in B^\tau$ satisfying the following properties:*

(1) $\phi(Z^\tau(u, v, a)) = e + uav^t \in \mathrm{E}(n, R)$, $(u, v, a) \in B^\tau$;
(2) $Z^1(u, v + w, a) = Z^1(u, v, a) \cdot Z^1(u, w, a)$;
(3) $Z^2(v + w, u, a) = Z^2(v, u, a) \cdot Z^2(w, u, a)$;
(4) for $\tau = 1, 2$ and $b \in R$ if $(u, vb, a), (ub, v, a) \in B^\tau$ then one has

$$Z^\tau(u, vb, a) = Z^\tau(u, v, ab) = Z^\tau(ub, v, a);$$

(5) ${}^g Z^\tau(u, v, a) = Z^\tau(\phi(g) \cdot u, \phi(g)^* \cdot v, a)$, $\tau = 1, 2$, $g \in \mathrm{St}^G(n, R)$.

Proof. One constructs the elements $Z^1(u, v, a)$ in exactly the same way as Tulenbaev constructs his elements $X_{u,v}(a)$ (see definitions preceding [11, Lemma 1.2]). Indeed, set

$$(A.1) \qquad Z^1(v, w, a) = \prod_{k=1}^{p} X(v, a \cdot w^k), \quad Z^2(w, v, a) = \prod_{k=1}^{p} X(a \cdot w^k, v).$$

where $X(u, v)$ denotes the elements defined by Tulenbaev before [11, Lemma 1.1].

The correctness of this definition and all the assertions of the lemma (with the exception of the last one in the case $n = 4$) can be proved by the same token as in [11, Lemma 1.3]. $\square$

For the rest of this section a denotes a nonnilpotent element of R and $\lambda_a \colon R \to R_a$ is the morphism of principal localization at a.

lem:rk3rels

Lemma A.4. *For any $g \in \mathrm{E}(n, R_a)$ there exist $u, v \in R^n$ and sufficiently large natural numbers k, m such that the following facts hold:*

(1) $\lambda_a(u) = g \cdot a^k e_1$, $\lambda_a(v) = g^* \cdot a^k e_2$ and $u^t \cdot v = 0$;
(2) $(u, v, a^m) \in B^1 \cap B^2$;
(3) for $b \in R$ divisible by some sufficiently large power of a one has

$$Z^1(u, b \cdot v, a^m) = Z^2(b \cdot u, v, a^m).$$

Proof. It is straightforward to choose u and v satisfying the first requirement of the lemma. We can even choose u, v in such a way that $u \in D(v)$ and $v \in D(u)$. Indeed, notice that $I(u) = a^{k_1}$, $I(v) = a^{k_2}$ for some natural k_1, k_2 hence for $u' = a^{k_2} \cdot u$ and $v' = a^{k_1} \cdot v$ one has

$$u' \in I(v) \cdot O(v) \subseteq D(v) \subseteq D(v'), \quad v' \in I(u) \cdot O(u) \subseteq D(u) \subseteq D(u'),$$

as required.

In fact, we can also choose two extra columns $x, y \in R^n$ and a large natural p in such a way that vectors u, v, x, y additionally satisfy the following properties

$$\lambda_a(x) = g^* \cdot a^k e_3, \ \lambda_a(y) = g \cdot a^k e_3, \ y^t \cdot x = a^p \in R,$$

$$u^t \cdot x = 0, \ u^t \cdot v = 0, \ y^t \cdot v = 0,$$

$$(u, x, a^m) \in B^1, \ (y, v, a^m) \in B^2.$$

Now direct computation using Lemma A.3 shows that

$$Z^2(a^{m+p}b \cdot u, v, a^m) = Z^2(b \cdot (e + a^m \cdot ux^t)y, (e - a^m \cdot xu^t)v, a^m) \cdot Z^2(-by, v, a^m) =$$
$$= [Z^1(u, x, a^m), Z^2(b \cdot y, v, a^m)] =$$
$$= Z^1(u, x, a^m) \cdot Z^1((e + a^m b \cdot yv^t)u, -(e - a^m b \cdot vy^t)x, a^m) = Z^1(u, a^{m+p}b \cdot v, a^m), \quad \square$$

hence the third assertion of the lemma follows.

cor:tulmap **Corollary A.5.** *[Tulenbaev's lemma] For $n \geq 4$ there is a map T_n so that the following diagram commutes.*

Proof. Follows from Lemma A.4 by the same token as in [11, Lemma 2.3]. $\square$

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