REPRESENTATIONS OF REDUCTIVE ALGEBRAIC GROUPS

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Contents

§1. GENERALITIES ON AFFINE GROUP SCHEMES AND SMOOTH REPRESENTATIONS

1.1. Affine group schemes Fix k a base field.

Recall that an **affine k-group scheme** is one of the following data:

(1) An affine scheme G over k endowed with morphisms of k-schemes
- $m : G \times G \to G$;
- $e : \mathrm{Spec}(k) \to G$;
- $\mathrm{inv} : G \to G$;

which satisfy the usual axioms of groups (with m multiplication, e the unit, inv the inverse).

(2) A functor $\mathsf{Alg}_k = \{k\text{-algebras}\} \xrightarrow{F} \mathsf{Gps}$ such that the composition $\mathsf{Alg}_k \xrightarrow{F} \mathsf{Gps} \to \mathsf{Sets}$ is representable.

(3) A commutative Hopf algebra over k, i.e. a commutative algebra A with morphisms of k-algebras
- $\Delta : A \to A \otimes A$;
- $\varepsilon : A \to k$;
- $S : A \to A$;

such that

$$(\mathrm{id} \otimes \Delta) \circ \Delta = (\Delta \otimes \mathrm{id}) : A \longrightarrow A \otimes A \otimes A$$
$$(\mathrm{id} \otimes \varepsilon) \circ \Delta = \mathrm{id} = (\varepsilon \otimes \mathrm{id}) \circ \Delta : A \longrightarrow A$$
$$(\mathrm{id}, S) \circ \Delta = \Delta \circ \varepsilon = (S, \mathrm{id}) \circ \Delta : A \longrightarrow A$$

Notation. —

$$A \longrightarrow \mathrm{Spec}(A)$$
$$G \longrightarrow \mathscr{O}(G), \Delta_G.$$

Example 1.1.1. —

(1) *Diagonalizable groups:* If Λ is an abstract commutative group we have the affine k-group scheme $\mathrm{Diag}(\Lambda) := \mathrm{Spec}(k[\Lambda])$ with

$$\Delta(\lambda) = \lambda \otimes \lambda, \quad \varepsilon(\lambda) = 1, \quad S(\lambda) = \lambda^{-1} \quad (\forall \lambda \in \Lambda).$$

In particular for $\Lambda = \mathbb{Z}$, $k[\Lambda] = k[x, x^{-1}]$ and $\mathrm{Diag}(\Lambda) = \mathbb{G}_m$ (the **multiplicative group**).

A **(split) torus** is a group scheme of the form $\mathrm{Diag}(\Lambda)$ with Λ a finitely generated free abelian group.

(2) *Additive group:* $\mathbb{G}_a := \mathrm{Spec}(k[x])$ with

$$\Delta(x) = x \otimes 1 + 1 \otimes x, \quad \varepsilon(x) = 0, \quad S(x) = -x.$$

More generally for V a k-vector space we have the functor $V_a : R \mapsto (R \otimes V, -)$ which is an affine k-group scheme if V is finite dimensional.

(3) If V is a k-vector space, $\mathbf{GL}(V)$ is the functor $R \mapsto \mathrm{Aut}_R(R \otimes V)$. If V is finite dimensional this is an affine k-group scheme.

In particular, if $V = k^n$ we get

$$\mathbf{GL}_n = \mathrm{Spec}(k[x_{ij}, 1 \leq i, j \leq n][\det^{-1}])$$

with

$$\Delta(x_{ij}) = \sum_l x_{il} \otimes x_{lj}, \quad \varepsilon(x_{ij}) = \delta_{ij}.$$

Similarly we have $\mathbf{SL}(V), \mathbf{SL}_n$.

(4) For any abstract group Γ we have the functor (??)

1.2. Representations If G is an affine k-group scheme, a **representation** of G is the datum of a k-vector space V and a morphism of group valued functors $G \to \mathbf{GL}(V)$. [Equivalently, an action of G on V_a such that $G(R)$ acts R-linearly on $R \otimes V$.]

This datum is equivalent ot that of a **comodule** for $\mathscr{O}(G)$, i.e. a k-vector space V and a k-linear map $\Delta_V : V \to V \otimes \mathscr{O}(G)$ such that

$$(\Delta_V \otimes \mathrm{id}_{\mathscr{O}(G)} \circ \Delta_V = (\mathrm{id}_V \otimes \Delta_G) \circ \Delta_V : V \longrightarrow V \otimes \mathscr{O}(G) \otimes \mathscr{O}(G)$$
$$(\mathrm{id}_V \otimes \varepsilon) \otimes \Delta_V = \mathrm{id}_V : V \longrightarrow V.$$

[Δ_V corresponds to the image of $\mathrm{id}_{\mathscr{O}(G)} \in G(\mathscr{O}(G)) = \mathrm{End}_{k\text{-alg}}(\mathscr{O}(G))$ in $\mathrm{End}_{\mathscr{O}(G)}(\mathscr{O}(G) \otimes V)$.]

Example 1.2.1. —

(1) *(Right) Regular representation:* $V = \mathscr{O}(G)$ with $\Delta_V = \Delta_G$. More generally, given an action of G on an affine scheme X we get a representation with underlying vector space $\mathscr{O}(X)$.
(2) If V is a finite dimensional vector space, V is a representation of $\mathbf{GL}(V)$.
(3) For any G we have the trivial representation k.

Notation. — $\mathrm{Rep}(G)$ is the abelian category of representations of G. $\mathrm{Rep}^{\mathrm{fd}}(G)$ is the full subcategory of finite dimensional representations.

If $V \in \mathrm{Rep}(G)$ then V is the union of its finite dimensional subrepresentations.

Example 1.2.2 (Representations of diagonalizable group schemes). — Let Λ be a commutative group, $G = \mathrm{Diag}(\Lambda)$. If $V \in \mathrm{Rep}(G)$ we have

$$\Lambda_V : V \longrightarrow V \otimes \mathscr{O}(G) = \bigoplus_{\lambda \in \Lambda} V \otimes \lambda.$$

Hence there are morphisms $(\rho_\lambda : \lambda \in \Lambda)$ in $\mathrm{End}(V)$ such that

$$\Delta_V(v) = \sum_{\lambda \in \Lambda} \rho_\lambda(v) \otimes \lambda, \qquad \forall v \in V.$$

(Here $\rho_\lambda(v) = 0$ for all but finitely many λs.)

It is easy to see that

$$\rho_\lambda \circ \rho_\mu = \begin{cases} \rho_\lambda & \text{if } \lambda = \mu \\ 0 & \text{otherwise} \end{cases}$$

and $\mathrm{id} = \sum_{\lambda_\Lambda} \rho_\lambda$.

Hence $V = \bigoplus_{\lambda \in \Lambda} \rho_\lambda(V)$ with

$$\rho_\lambda(V) = \{v \in V : \Delta_V(v) = v \otimes \lambda\} = V_\lambda.$$

Hence $\mathrm{Rep}(G)$ is isomorphic to the category of Λ-graded vector spaces (correct?).

1.3. Induction Let G be an affine k-group scheme.

A **subgroup** of G is a closed subscheme $H \subset G$ such that $e, \mathrm{inv}\,|_H, m|_{H \times H}$ factor through H. Then H is an affine k-group scheme. In this setting we have the restriction functor $\mathrm{Res}^G_H : \mathrm{Rep}(G) \to \mathrm{Rep}(H)$.

Proposition 1.3.1. — *The functor* Res^G_H *has a right adjoint* $\mathrm{Ind}^G_H : \mathrm{Rep}(H) \to \mathrm{Rep}(G)$.

Explicitly, we have

$$\mathrm{Ind}^G_H(V) = (V \otimes \mathscr{O}(G))^H$$

with H acting diagonally via the right-regular representation on $\mathscr{O}(G)$ and G acting on the fixed points via the left regular representation

$$\mathrm{Ind}^G_H(V) = \left\{ \begin{array}{c} \text{morphisms of functors} \\ f : G \to V_a \end{array} \;\middle|\; \begin{array}{c} f(gh) = h^{-1} f(g) \\ \forall g \in G(R), h \in H(R), R \in \mathsf{Alg}_k \end{array} \right\}.$$

The canonical isomorphism

$$\mathrm{Hom}_{\mathrm{Rep}(G)}(V, \mathrm{Ind}^G_H(V')) \simeq \mathrm{Hom}_{\mathrm{Rep}(H)}(V, V')$$

is called **Frobenius reciprocity**.

Properties. —

- *Transitivity:* Given subgroups $H_1 \subset H_2 \subset G$ we have
$$\mathrm{Ind}_{H_1}^G \simeq \mathrm{Ind}_{H_2}^G \circ \mathrm{Ind}_{H_1}^{H_2}.$$
- *Tensor identity:* For $V_1 \in \mathrm{Rep}(H), V_2 \in \mathrm{Rep}(G)$
$$\mathrm{Ind}_H^G(V_1 \otimes \mathrm{Res}_H^G(V_2)) \simeq \mathrm{Ind}_H^G(V_1) \otimes V_2.$$
- Ind_H^G sends injective objects of $\mathrm{Rep}(H)$ to injective objects of $\mathrm{Rep}(G)$. In particular,
$$\mathrm{Ind}_H^G(k) = \mathscr{O}(G)$$
is injective.
- $\mathrm{Rep}(G)$ has enough injectives.

Geometric interpretation: We assume G is an algebraic group (over k), i.e. an affine k-group scheme such that $\mathscr{O}(G)$ is a finitely generated k-algebra. In this setting, for $H \subset G$ a subgroup we have a quotient scheme G/H of finite type over k with a faithfully flat quotient map $\pi : G \to G/H$. For $V \in \mathrm{Rep}(H)$, we have a quasicoherent sheaf $\mathscr{L}_{G/H}(V) \in \mathsf{QCoh}(G/H)$ with
$$\Gamma(V, \mathscr{L}_{G/H}(V)) = \left\{ \text{morphisms } f : \pi^{-1}(V) \longrightarrow V \,\middle|\, f(x,h) = h^{-1} f(x) \text{ for all } (?) \right\}.$$
We have $\mathrm{Ind}_H^G(V) = \Gamma(G/H, \mathscr{L}_{G/H}(V))$. If V is finite dimensional, then $\mathscr{L}_{G/H}(V)$ is coherent.

Consequences. —

- If G/H is affine then Ind_H^G is exact.
- If G/H is projective then Ind_H^G preserves finite dimensionality.

Since $\mathrm{Rep}(H)$ has enough injectives we can consider the derived functor
$$\mathrm{R}\,\mathrm{Ind}_H^G : D^b\,\mathrm{Rep}(H) \longrightarrow D^b\,\mathrm{Rep}(G).$$
The functor $\mathscr{L}_{G/H} : \mathrm{Rep}(H) \to \mathsf{QCoh}(G/H)$ is exact, hence we have
$$\mathscr{L}_{G/H} : D^b\,\mathrm{Rep}(H) \longrightarrow D^b\mathsf{QCoh}(G/H).$$
One can check that
$$\mathrm{R}\,\mathrm{Ind}_H^G(V) \simeq R\Gamma(G/H, \mathscr{L}_{G/H}(V)).$$
(??)

Consequences. —

- We have $\mathrm{R}^n\,\mathrm{Ind}_H^G(V) = 0$ for all $V \in \mathrm{Rep}(H)$ if $n > \dim(G/H)$.
- If G/H is projective, then $\mathrm{R}^n\,\mathrm{Ind}_H^G(V)$ is finite-dimensional for all $V \in \mathrm{Rep}^{\mathrm{fd}}(H), n \in \mathbb{Z}$.

§2. REDUCTIVE ALGEBRAIC GROUPS

From now on k is algebraically closed.

2.1. Definition A k-algebraic group G is called **unipotent** if every non-zero representation admits a non-zero fixed vector. [Equivalent condition: G is unipotent if and only if it is isomorphic to a subgroup of unipotent upper-triangular matrices in $\mathbf{GL}_n$ for some n.]

Example 2.1.1. — $\mathbb{G}_a$ is unipotent as

$$\mathbb{G}_a \simeq \begin{pmatrix} 1 & * \\ 0 & 1 \end{pmatrix}.$$

If G is a smooth, connected algebraic group, the smooth, connected, unipotent, normal subgroups of G there is a largest element called the **unipotent radical** of G, denoted $R_u(G)$. An algebraic group G is called **reductive** if it is smooth, connected and $R_u(G)$ is trivial.

One possible motivation for studying representations of reductive algebraic groups is that any simple representation of a smooth connected algebraic group G factors through a simple representation of $G/R_u(G)$, which is a reductive algebraic group.

Example 2.1.2. —

(1) *Tori:* If Λ is a finitely generated, free abelian group, then $\mathrm{Diag}(\Lambda)$ is a reductive algebraic group.
(2) For any finite-dimensional k-vector space V, $\mathbf{GL}(V)$ and $\mathbf{SL}(V)$ are reductive algebraic groups.
(3) Symplectic groups, special orthogonal groups.

2.2. Structure From now on G is a redutive algebraic group.

We denote by B a **Borel subgroup** (a maximal, connected, smooth, solvable subgroup). Note that:

- a Borel subgroup is unique up to conjugation;
- the quotient G/B is a smooth, projective variety.

Example 2.2.1 (Main Example). — For $G = \mathbf{GL}_{n,k}$ one can take

$$B = \left\{ \begin{pmatrix} * & & 0 \\ & \ddots & \\ * & & * \end{pmatrix} \right\}.$$

In this case G/B parametrizes flags in k^n, i.e. data

$$\{0\} \subset V_1 \subset \cdots \subset V_{n-1} \subset k^n$$

with V_i a subspace of dimension i.

Let T be a maximal torus contained in B.

Example 2.2.2 (Main Example Continued). — We take

$$T = \left\{ \begin{pmatrix} t_1 & & 0 \\ & \ddots & \\ 0 & & t_n \end{pmatrix} \right\}.$$

Note that

$$T \simeq \mathrm{Diag}(\mathbb{X}), \quad \mathbb{X} = \{\text{morphisms } T \longrightarrow \mathbb{G}_m\}$$

we call elements of $\mathbb{X}$ **weights**.

Example 2.2.3 (Main Example Continued). — For example, $X \simeq \mathbb{Z}^n$ via

$$(\lambda_1, \ldots, \lambda_n) \leftrightarrow \begin{pmatrix} t_1 & & 0 \\ & \ddots & \\ 0 & & t_n \end{pmatrix} \longmapsto \prod_{i=1}^{n} t_i^{\lambda_i}.$$

The **roots** $R \subset \mathbb{X}$ are the non-zero weights appearing in the action of T on $\mathfrak{g} = \mathrm{Lie}(G)$. For example,

$$R = \{\varepsilon_i - \varepsilon_j : 1 \leq i \neq j \leq n\}.$$

We have $R_+ \subset R$ the positive roots: the weights appearing in the action of T on $\mathfrak{g}/\,\mathrm{Lie}(B)$. We have the simple roots $R_s \subset R_+$: positive roots that cannot be written as a sum of two positive roots.

Note. — $R = R_+ \coprod -R_+$. Any element of R_+ can be uniquely written as a sum of simple roots.

For example,

$$\begin{aligned} R_+ &= \{\varepsilon_i - \varepsilon_j : 1 \leq i < j < n\} \\ R_s &= \{\varepsilon_i - \varepsilon_{i+1}\}. \end{aligned}$$

We also set

$$\begin{aligned} \mathbb{X}^\vee &= \mathrm{Hom}_{\mathbb{Z}}(\mathbb{X}, \mathbb{Z}) \\ &= \{\text{morphisms } \mathbb{G}_m \longrightarrow T\}. \end{aligned}$$

We have the coroots $R^\vee \subset \mathbb{X}^\vee$ and a bijection

$$\begin{aligned} R &\longrightarrow R^\vee \\ \alpha &\longmapsto \alpha^\vee. \end{aligned}$$

Then $(\mathbb{X}, R, \mathbb{X}^\vee, R^\vee)$ together with the identification $\mathbb{X}^\vee = \mathrm{Hom}(\mathbb{X}, \mathbb{Z})$ and the bijection $R \to R^\vee$ is the **root datum** of G. It determines G up to isomorphism.

We have the opposite Borel subgroup $B^+ \subset G$ containing T such that the non-zero weights of T acting on $\mathrm{Lie}(B^+)$ are R_+.

$W = N_G(T)/T$ is the **Weyl group**. This is a contant group scheme, associated with a finite group also denoted W. We have a faithful action of W on $\mathbb{X}$. For $\alpha \in R$ there is an element $s_\alpha \in W$ which acts on $\mathbb{X}$ via

$$\lambda \longmapsto \lambda - \langle \lambda, \alpha^\vee \rangle \alpha.$$

Set

$$S = \{s_\alpha : \alpha \in R_s\} \subset W.$$

Then (W, S) is a Coxeter system.

In particular, we have the length function

$$\begin{aligned} \ell : W &\longrightarrow \mathbb{Z}_{\geq 0} \\ w &\longmapsto \min\{r \geq 0 | \text{there exist } s_1, \ldots, s_r \in S \text{ such that } w = s_1 \cdots s_r\}. \end{aligned}$$

For example, $W = \mathfrak{S}_n$ is the symmetric group via permutation matrices. The action on $\mathbb{X} = \mathbb{Z}^n$ is by permuting entries

$$S = \{(i, i+1) : 1 \leq i < n\}.$$

The length function counts inversions of permutations.

Example 2.2.4. — Let $G = \mathbf{SL}_2$,

$$\begin{aligned} B &= \left\{ \begin{pmatrix} * & 0 \\ * & * \end{pmatrix} \right\} \subset \mathbf{SL}_{2,k} \\ T = T &= \left\{ \begin{pmatrix} t & 0 \\ 0 & t^{-1} \end{pmatrix} \middle| t \in k^\times \right\} \simeq \mathbb{G}_m. \end{aligned}$$

We have $\mathbb{X} \simeq \mathbb{Z}$ via

$$\lambda \leftrightarrow \left[\begin{pmatrix} t & 0 \\ 0 & t^{-1} \end{pmatrix} \longmapsto t^\lambda \right].$$

We have $R = \{2, -2\}$, $R_+ = \{2\} = R_s$ and $W = \mathfrak{S}_2 = \mathbb{Z}/2\mathbb{Z}$.

2.3. Classification of simple representations We have $B = T \ltimes U$ with $U = R_u(B)$ and $B^+ = T \ltimes U^+$ with $U^+ = R_u(B^+)$. In particular, $T \xrightarrow{\sim} B/U$, so any $\lambda \in \mathbb{X}$ provides a morphism $B \to \mathbb{G}_m$. We have a one-dimensional representation $k_B(\lambda)$. We set

$$\nabla(\lambda) = \mathrm{Ind}_B^G(k_B(\lambda)).$$

It's easy to see that:

- $\dim(\nabla(\lambda)) < \infty$ for all $\lambda \in \mathbb{X}$ (because G/B is projective).
- The action of T on $\nabla(\lambda)$ determines an $\mathbb{X}$-grading

  $$\nabla(\lambda) = \bigoplus_{\mu \in \mathbb{X}} \nabla(\lambda)_\mu.$$

  Here if $\nabla(\lambda) \neq 0$, we have
  - $\nabla(\lambda)_\lambda = \nabla(\lambda)^{U^+}$ and this is one-dimensional,
  - if $\nabla(\lambda)_\mu \neq 0$ then $\lambda - \mu \in \mathbb{Z}_{\geq 0} R_s$.

  This follows from the open embedding

  $$U^+ \times B \hookrightarrow G$$

  induced by multiplication.

Corollary 2.3.1. — *We have a bijection*

$$\begin{aligned} \{\lambda \in \mathbb{X} | \nabla(\lambda) \neq 0\} &\xrightarrow{\sim} \{\textit{simple objects in } \mathrm{Rep}(G)\} / \simeq \\ \lambda &\longmapsto L(\lambda) = \textit{ unique simple subrepresentation in } \nabla(\lambda). \end{aligned}$$

It's less easy to show:

Proposition 2.3.1. — *For $\lambda \in \mathbb{X}$, we have*

$$\nabla(\lambda) \neq 0 \quad \iff \quad \forall \alpha \in R_s, \langle \lambda, \alpha^\vee \rangle \geq 0.$$

Idea of the proof. The forward direction is easy using the fact that W permutes

$$\left\{ \mu \in \mathbb{X} \middle| \nabla(\lambda)_\mu \neq 0 \right\}.$$

Conversely, one can construct a function

$$\bigcup_{\alpha \in R_s} s_\alpha U^+ B \longrightarrow k$$

and then use the fact that the LHS has complement of codimension 2 in G, cf. Bruhat decomposition. □

We set

$$\mathbb{X}_+ = \left\{ \lambda \in \mathbb{X} \middle| \forall \alpha \in R_s, \langle \lambda, \alpha^\vee \rangle \geq 0 \right\}$$

the **dominant weights**.

Example 2.3.1. — (1) $\nabla(0) = k$ is the trivial representation (because G/B is connected and projective).

(2) Let $G = \mathbf{GL}_{n,k}$

$$\mathbb{X}_+ = \{(\lambda_1, \dots, \lambda_n) | \lambda_1 \geq \lambda_2 \geq \dots \geq \lambda_n\}.$$

For $r \geq 0$

$$\nabla(r, 0, \dots, 0) \simeq S^r(V)$$

with $V = k^n$ the natural representation, and

$$\nabla(0, \dots, 0, -r) \simeq S^r(V^*)$$

(cf. sections of line bundles on $\mathbb{P}^n$).

For $s \in \{1, \dots, n\}$,

$$\begin{aligned}\nabla(\underbrace{1, \dots, 1}_{s}, 0, \dots, 0) &= \bigwedge^{s}(V) \\ &= L(\underbrace{1, \dots, 1}_{s}, 0, \dots, 0).\end{aligned}$$

For $r \in \mathbb{Z}$

$$\nabla(r, \dots, r) = k_{\det^r} = L(r, \dots, r).$$

(3) Let $G = \mathbf{SL}_2$, then $\mathbb{X}_+ = \mathbb{Z}_{\geq 0}$. For $r \geq 0$

$$\nabla(r) = S^r(k^2)$$

(cf. sections of line bundles on $G/B = \mathbb{P}^1$). If $\mathrm{char}(k) = 0$ then $\nabla(r)$ is simple for all $r \geq 0$. If $\mathrm{char}(k) = p > 0$ this is not always true:

$$\nabla(p) = kx^p \oplus kx^{p-1}y \oplus \cdots \oplus kxy^{p-1} \oplus ky^p$$

with x, y a canonical basis of k^2. Then $kx^p \oplus ky^p$ is a non-trivial G-stable subspace. In fact, $L(p) = kx^p \oplus ky^p$.

More generally, $\nabla(r)$ is simple if and only if $r \leq p - 1$.

(4) For all $\lambda \in \mathbb{X}_+$, $L(\lambda)^* \simeq L(-w_0\lambda)$ where $w_0 \in W$ is the longest element.

2.4. Characters If $V \in \mathrm{Rep}^{\mathrm{fd}}(G)$ then the action of T determines a grading $V = \bigoplus_{\lambda \in \mathbb{X}} V_\lambda$ with

$$V_\lambda = \{v \in V | \forall t \in T, tv = \lambda(t)v\}.$$

We set

$$\mathrm{ch}(V) = \sum_{\lambda \in \mathbb{X}} \dim(V_\lambda) e^\lambda \in \mathbb{Z}[\mathbb{X}].$$

It's easy to check that:

- ch factors through $K^0(\mathrm{Rep}^{\mathrm{fd}}(G)) \to \mathbb{Z}[\mathbb{X}]$.
- $\mathrm{ch}(V \otimes V') = \mathrm{ch}(V)\,\mathrm{ch}(V')$, so the map above is a *ring morphism*.
- ch takes values in $\mathbb{Z}[\mathbb{X}]^W$.

Proposition 2.4.1. — ch *induces an isomorphism*

$$K^0(\mathrm{Rep}^{fd}(G)) \xrightarrow{\sim} \mathbb{Z}[\mathbb{X}]^W.$$

Proof idea. Show that

$$\{\mathrm{ch}(L(\lambda)) | \lambda \in \mathbb{X}_+\}$$

is a basis of $\mathbb{Z}[\mathbb{X}]^W$. □