

8. VECTORBUNDLES AND SYSTEMS

Objektyp: **Chapter**

Zeitschrift: **L'Enseignement Mathématique**

Band (Jahr): **29 (1983)**

Heft 1-2: **L'ENSEIGNEMENT MATHÉMATIQUE**

PDF erstellt am: **28.04.2024**

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Then using the results above one shows that

$$\underline{t} \, \underline{s}(\overline{0(\kappa)}) = \overline{0(\kappa)}, \underline{s} \, \underline{t}(\overline{U(\kappa)}) = \overline{U(\kappa)}$$

so that $\underline{t}$ and $\underline{s}$ set up a bijective correspondence between the closures of orbits in the two cases and hence induce a bijective order preserving correspondence between the sets of orbits themselves.

8. VECTORBUNDLES AND SYSTEMS

This section contains a modified version of the construction of Hermann-Martin [14] associating a vectorbundle $E(\Sigma)$ over the Riemann sphere $\mathbf{P}^1(\mathbf{C})$ to every $\Sigma = (A, B) \in L_{m,n}^{cr}$. This version makes it almost trivial to see that $E(\Sigma)$ splits as a direct sum of line bundles $L(\kappa_i)$, $i = 1, \dots, m$ where $\kappa = (\kappa_1, \dots, \kappa_m)$ is the set of Kronecker indices of Σ .

The first thing needed is some more information on the universal bundle ξ_m .

8.1. *On the Universal Bundle* $\xi_m \rightarrow \mathbf{G}_n(\mathbf{C}^{n+m})$. Let V be a complex $n + m$ dimensional vector space and $V^* = \text{Hom}_{\mathbf{C}}(V, \mathbf{C})$ its dual vector space. Given $x \in \mathbf{G}_n(\mathbf{C}^{n+m})$ define $x^* = \{y \in V^* \mid \langle y, v \rangle = 0 \text{ for all } v \in x\}$ where $\langle \cdot, \cdot \rangle$ denotes the usual pairing $V^* \times V \rightarrow \mathbf{C}$. Then x^* is m -dimensional and $x \mapsto x^*$ defines a holomorphic isomorphism

$$(8.2) \quad d : \mathbf{G}_n(V) \rightarrow \mathbf{G}_m(V^*).$$

Now $v \in V/x$ defines a unique homomorphism $v^T : x^* \rightarrow \mathbf{C}$ as follows:

$v^T(a) = \langle a, \tilde{v} \rangle$ for all $a \in x^*$, where $\tilde{v} \in V$ is any representative of v . This is well defined because $\langle a, b \rangle = 0$ for all $b \in x$ if $a \in x^*$. This defines an isomorphism between the pullback $(d^{-1}) \xi_m$ and the dual of the subbundle η_m on $\mathbf{G}_m(V^*)$ defined by

$$\eta_m = \{(x^*, w) \in \mathbf{G}_m(V^*) \times V^* \mid w \in x^*\}$$

It follows that ξ_m is a subbundle of an $n + m$ dimensional trivial bundle $\mathbf{G}_n(\mathbf{C}^{n+m}) \times \mathbf{C}^{n+m}$. Because $\mathbf{G}_n(\mathbf{C}^{n+m})$ is projective (compact) all holomorphic maps $\mathbf{G}_n(\mathbf{C}^{n+m}) \rightarrow \mathbf{C}$ are constant so that the space of holomorphic sections $\Gamma(\mathbf{G}_n(\mathbf{C}^{n+m}) \times \mathbf{C}^{n+m}, \mathbf{G}_n(\mathbf{C}^{n+m}))$ is of dimension $n + m$. As a subbundle of a trivial $(n + m)$ -dimensional bundle ξ_m can therefore have at most $(n + m)$ linearly

independent holomorphic sections. But we have already found $(n+m)$ linearly independent sections viz. the $\varepsilon_1, \dots, \varepsilon_{n+m}$ defined by $\varepsilon_i(x) = e_i \bmod x$ where e_i is the i -th standard basis vector of $\mathbb{C}^{n+m}$. Therefore

$$(8.3) \quad \dim \Gamma(\xi_m, \mathbf{G}_n(\mathbb{C}^{n+m})) = n + m$$

Now let $A \in \mathbf{GL}_{n+m}(\mathbb{C})$. Then A induces a holomorphic automorphism A^* of $\mathbf{G}_m(\mathbb{C}^{n+m})$ defined by $x \mapsto Ax$. Then, of course, there is an induced isomorphism $A^{-1} : \mathbb{C}^{n+m}/Ax \rightarrow \mathbb{C}^{n+m}/x$ which for varying x induces an isomorphism

$$(8.4) \quad A_* \xi_m \simeq \xi_m, A \in \mathbf{GL}_{n+m}(\mathbb{C})$$

8.5. *The Line Bundles $L(i)$ over $\mathbf{P}^1(\mathbb{C})$.* The Riemann sphere $\mathbf{P}^1(\mathbb{C}) = S^2$ can be obtained by gluing together two copies of $\mathbb{C}$ along the open subsets $\mathbb{C} \setminus \{0\}$ by the isomorphism

$$\mathbb{C} \setminus \{0\} \rightarrow \mathbb{C} \setminus \{0\}, s \mapsto t = s^{-1}$$

A line bundle over $\mathbf{P}^1(\mathbb{C})$ is then obtained by giving a holomorphic isomorphism $\mathbb{C} \setminus \{0\} \times \mathbb{C} \rightarrow \mathbb{C} \setminus \{0\} \times \mathbb{C}$ linear in the second variable compatible with the above isomorphism. Obviously the only possibilities are $(s, v) \rightarrow (s^{-1}, s^i v)$ for $i \in \mathbb{Z}$. This gives us the following commutative diagram identifications

$$\begin{array}{ccccc} \mathbb{C} \times \mathbb{C} \supset \mathbb{C} \setminus \{0\} \times \mathbb{C} & \xrightarrow{\quad} & \mathbb{C} \setminus \{0\} \times \mathbb{C} \subset \mathbb{C} \times \mathbb{C} \\ \uparrow s_1 & \downarrow & \downarrow & \downarrow & \uparrow s_2 \\ \mathbb{C} \supset \mathbb{C} \setminus \{0\} & \xrightarrow{\quad} & \mathbb{C} \setminus \{0\} & \subset \mathbb{C} & \end{array}$$

$(s, v) \rightarrow (s^{-1}, s^i v)$
 $s \rightarrow s^{-1} = t$

The corresponding holomorphic line bundle is denoted $L(-i)$. A section of $L(-i)$ consists of two holomorphic mappings s_1, s_2 of the form $s \rightarrow (s, f(s)), t \rightarrow (t, g(t))$ such that $s^i f(s) = g(s^{-1})$. It readily follows that $f(s)$ must be a polynomial of degree $\leq -i$. Thus

$$(8.6) \quad \dim \Gamma(L(i)) = 0 \quad \text{if } i < 0$$

$$(8.7) \quad \dim \Gamma(L(i)) = i + 1 \quad \text{if } i \geq 0$$

8.8. *The (modified) Hermann-Martin vectorbundle of a system.* Let $\Sigma = (A, B)$ be a pair of real or complex matrices of sizes $n \times n$ and $n \times m$. Then (A, B) is completely reachable (cr) iff the $n \times (n+m)$ matrix $(sI - A; B)$ is of rank n for all complex values of s . So if $\Sigma = (A, B)$ is cr one can define a holomorphic map ψ_Σ by

$$(8.9) \quad \psi_{\Sigma} : \mathbf{P}^1(\mathbf{C}) \rightarrow \mathbf{G}_n(\mathbf{C}^{n+m}), s \mapsto \text{Row}(sI - A; B), \infty \mapsto \text{Row}(I; 0)$$

where $\text{Row}(M)$ for an $n \times (m+n)$ matrix M denotes the subspace of $\mathbf{C}^{n+m}$ generated by the rows of M . The vectorbundle $E(\Sigma)$ over $\mathbf{P}^1(\mathbf{C})$ is now defined by

$$(8.10) \quad E(\Sigma) = \psi_{\Sigma}^! \xi_m$$

8.11. *Proposition.* $E(\Sigma)$ depends only on the feedback orbit of Σ .

Indeed one easily checks that $\Sigma = (A, B), \Sigma' = (A', B') \in L_{m,n}^{cr}$ are feedback equivalent (cf. 2.6 above) iff there are constant invertible matrices P, Q such that

$$P(sI - A; B)Q = (sI - A'; B').$$

Now $\text{Row}(PM) = \text{Row}(M)$ and postmultiplication with Q changes ψ_{Σ} to $Q_* \circ \psi_{\Sigma}$ and

$$E(\Sigma') = \psi_{\Sigma'}^! (\xi_m) = \psi_{\Sigma}^! (Q_* \xi_m) \simeq (\psi_{\Sigma}^! (\xi_m)) = E(\Sigma)$$

by 8.4 above, proving the proposition.

Thus to determine $E(\Sigma)$ we can assume that $\Sigma = (A, B)$ is in Brunowsky canonical form which means that A, B takes the form

$$\left[\begin{array}{ccc|ccc} 0 & 1 & 0 & & & \\ & & 1 & & & \\ 0 & & 0 & & & \\ \hline & & & 0 & 1 & 0 \\ & & & & & 1 \\ & & & 0 & & 0 \\ \hline & & & & & & 0 & 1 & 0 \\ & & & & & & & & 1 \\ & & & & & & 0 & & 0 \end{array} \right] \quad \left[\begin{array}{ccc} 0 & 0 & 0 \\ 0 & & \\ 1 & 0 & 0 \\ \hline 0 & 0 & 0 \\ & & 0 \\ 0 & 1 & 0 \\ \hline 0 & 0 & 0 \\ & & 0 \\ 0 & 0 & 1 \end{array} \right] \quad \begin{array}{l} \kappa_1 \\ \kappa_2 \\ \kappa_3 \end{array}$$

in case $m = 3$, where $(\kappa_1, \kappa_2, \kappa_3) = \kappa(A, B)$ are the Kronecker indices of $\Sigma = (A, B)$. (The general case is evident from this example); every $(A, B) \in U(\kappa)$ is feedback equivalent to such a pair [30, 9]. The matrix $(sI - A; B)$ is now easily written down, and one observes that for all

$$s \neq 0, \infty, e_1 \equiv e_2 \equiv \dots \equiv e_{\kappa_1} \equiv e_{n+1} \pmod{\text{Row}(sI - A; B)},$$

i.e. mod $\psi_\Sigma(s)$ and for $s = 0$, $e_2 \equiv \dots \equiv e_{\kappa_1} \equiv e_{n+1} \equiv 0$ but $e_1 \neq 0$ and for $s \equiv \infty$, $e_1 \equiv \dots \equiv e_{\kappa_1} \equiv 0$ and $e_{n+1} \neq 0$. It follows that the vectors

$$\varepsilon_1(\psi_\Sigma(s)), \dots, \varepsilon_{\kappa_1}(\psi_\Sigma(s)), \varepsilon_{n+1}(\psi_\Sigma(s))$$

span a one-dimensional subspace of $\xi_m(\psi_\Sigma(s))$ for all s so that $E(\Sigma) \simeq \psi_\Sigma^! \xi_m$ contains a line bundle L_1 which admits at least $\kappa_1 + 1$ linearly independent holomorphic sections viz. the $\varepsilon_1, \dots, \varepsilon_{\kappa_1}, \varepsilon_{n+1}$. Similar relations hold for

$$\varepsilon_{\kappa_1 + \dots + \kappa_{i-1} + 1}, \dots, \varepsilon_{\kappa_1 + \dots + \kappa_i}, \varepsilon_{n+1}$$

for all $i = 1, \dots, m$ giving us subbundles L_i , $i = 1, \dots, m$ which admit at least $\kappa_i + 1$ linearly independent holomorphic sections. This exhausts the ε_i and because the $\varepsilon_1(x), \dots, \varepsilon_{n+m}(x)$ span $\xi_m(x)$ for all $x \in \mathbf{G}_n(\mathbf{C}^{n+m})$ it follows that $E(\Sigma) = \bigoplus L_i$. As the pullback of the bundle ξ_m , $E(\Sigma)$ itself is a subbundle of an $(n+m)$ -dimensional trivial bundle. Because $\mathbf{P}^1(\mathbf{C})$ is projective it follows (as before) that $E(\Sigma)$ has at most $n + m$ linearly independent holomorphic sections. But L_i has at least $\kappa_i + 1$ linearly independent sections, hence $\bigoplus L_i$ has at least $\sum(\kappa_i + 1) = n + m$ linearly independent sections which proves that L_i has precisely $\kappa_i + 1$ linearly independent sections and hence identifies L_i as the bundle $L(\kappa_i)$ described above in (8.5). We have reproved the theorem of Hermann and Martin [14].

8.12. *Theorem.* Keeping the notations introduced above in (8.10) and (8.5) we have $E(\Sigma) \simeq \bigoplus_{i=1}^m L(\kappa_i)$.

Still another proof of this theorem, using the Riemann-Roch theorem is found in Byrnes [33].

8.13. *The Correspondence B.* (cf. the diagram in section 5 above). The mapping $\Sigma \mapsto E(\Sigma)$ is obviously continuous. Thus the result $\overline{U(\kappa)} \supset U(\lambda) \leftrightarrow \kappa > \lambda$ can be deduced from Shatz's theorem (cf. 2.9). Inversely Shatz's theorem for positive bundles over $\mathbf{P}^1(\mathbf{C})$ can be deduced from the result on feedback orbits because every positive bundle arises as an $E(\Sigma)$. By tensoring with a suitable $L(r)$, r high enough, the result is then extended to arbitrary bundles over $\mathbf{P}^1(\mathbf{C})$.

9. VECTORBUNDLES, SYSTEMS AND SCHUBERT CELLS

9.1. *Partitions and Schubert-cells.* Let κ be a partition of n . To κ we associate the following increasing sequence of n numbers $\tau(\kappa)$.