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$G_2$-Geometry of Overdetermined Systems of Second Order

By

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Introduction.

Discovery of E. Cartan in


Overdetermined (involutive) system:

\[
\frac{\partial^2 z}{\partial x^2} = \frac{1}{3} \left( \frac{\partial^2 z}{\partial y^2} \right)^3, \quad \frac{\partial^2 z}{\partial x \partial y} = \frac{1}{2} \left( \frac{\partial^2 z}{\partial y^2} \right)^2.
\]

Single equation of Goursat type:

\[
(B) \quad 9r^2 + 12t^2(rt - s^2) + 32s^3 - 36rst = 0,
\]

where

\[
r = \frac{\partial^2 z}{\partial x^2}, \quad s = \frac{\partial^2 z}{\partial x \partial y}, \quad t = \frac{\partial^2 z}{\partial y^2}.
\]

14-dimensional Exceptional Simple Lie Algebra $G_2$

The Plan of This TALK

Main Theme Contact Geometry of Second Order
• Grassmannian Construction of Jet Spaces (§1) 
\[ \Rightarrow PD\text{-manifolds (§4).} \]

• Geometry of Linear Differential Systems (Tanaka Theory) (§2) 
\[ \Rightarrow \text{Differential Systems associated with SGLA (Simple Graded Lie Algebras) (§3).} \]

• Link between them 
\[ \Rightarrow \text{Reduction Theorems for PD manifolds (§4, §5)} \]

Together combined to discuss

\[ G_{2}\text{-Geometry of Overdetermined Systems of Second Order (§6)} \]

§1. Second Order Contact Manifolds.

Grassmann Bundle:

\[ M: \text{a manifold of dimension } m + n \]

\[ J(M, n) = \bigcup_{x \in M} J_x, \quad J_x = \text{Gr}(T_x(M), n). \]

Canonical System \( C \) on \( J(M, n) \):

\[ \forall u \in J(M, n) \]

\[ C(u) = \pi_{o}^{-1}(u) \subset T_u(J(M, n)). \]

Inhomogeneous Grassmann coordinate: \( x_{o} = \pi(u_{o}) \in U' \); \((x_{1}, \cdots, x_{n}, z^{1}, \cdots, z^{m})\)

\[ U = \{ u \in \pi^{-1}(U') \mid \pi(u) = x \in U' \text{ and } dx_1 \wedge \cdots \wedge dx_n |_u \neq 0 \}; \]

Coordinates \((x_{1}, \cdots, x_{n}, z^{1}, \cdots, z^{m}, p_{1}^{1}, \cdots, p_{n}^{m})\) are introduced by

\[ dz^{\alpha} |_{u} = \sum_{i=1}^{n} p_{i}^{\alpha}(u) dx_{i} |_{u}. \]

On a canonical coordinate system \((x_{1}, \cdots, x_{n}, z^{1}, \cdots, z^{m}, p_{1}^{1}, \cdots, p_{n}^{m})\)

\[ C = \{ \omega^{1} = \cdots = \omega^{m} = 0 \}, \]

where \( \omega^{n} = dz^{n} - \sum_{i=1}^{n} p_{i}^{n} dx_{i}. \)

\[ m = 1 \Rightarrow \text{Contact Manifold} \]

\[ \varphi: M \rightarrow \hat{M}: \text{diffeomorphism} \Rightarrow \varphi_{*}: (J(M, n), C) \rightarrow (J(\hat{M}, n), \hat{C}) \]
Theorem 2.1 (Bäcklund). $M, \hat{M} :$ manifolds of dimension $m + n$. Assume $m \geq 2$. $\Phi : (J(M, n), C) \rightarrow (J(\hat{M}, \hat{C})$; isomorphism$\Rightarrow \exists \varphi : M \rightarrow \hat{M}$ such that $\Phi = \varphi_{*}$.

$$(J, C) : \text{Contact Manifold} \Rightarrow (L(J), E)$$

Lagrange-Grassmann Bundle

\[ L(J) = \bigcup_{u \in J} \pi_{u} \rightarrow J \]

\[ L_u = \{ \text{Legendrian subspaces of} (C(u), d\omega) \} \]

$\forall \nu \in L(J)$

\[ E(\nu) = \pi_{\nu}^{-1}(\nu) \subset T_{\nu}(L(J)) \xrightarrow{\pi_{\nu}} T_{\nu}(J) \]

where $(x_1, \cdots, x_n, z, p_1, \cdots, p_n, p_{11}, \cdots, p_{nn})$ and $p_{ij} = p_{ji}$

\[ E = \{ \omega = \omega_1 = \cdots = \omega_n = 0 \}, \]

where

\[
\begin{aligned}
\omega &= dz - \sum_{i=1}^{n} p_i \, dx_i, \\
\omega_i &= dp_i - \sum_{j=1}^{n} p_{ij} \, dx_j
\end{aligned}
\]

Theorem 2.2. $\Phi : (L(J), E) \rightarrow (L(\hat{J}), \hat{E})$; isomorphism $\Rightarrow \exists \varphi : (J, C) \rightarrow (\hat{J}, \hat{C})$ such that $\Phi = \varphi_{*}$.


$M$: a manifold of dimension $d$

$D \subset T(M)$: subbundle of rank $r$ ($s + r = d$)

\[ D = \{ \omega_1 = \cdots = \omega_s = 0 \}. \]

$(M, D)$: completely integrable

\[ \iff D = \{ dx_1 = \cdots = dx_s = 0 \} \]

\[ \iff d\omega_i \equiv 0 \pmod{\omega_1, \ldots, \omega_s} (1 \leq i \leq s) \]

\[ \iff [D, D] \subset D \text{ where } D = \Gamma(D) \]

Derived System $\partial D$: $\partial D = D + [D, D]$.

Cauchy Characteristic System $Ch(D)$:

\[ Ch(D)(x) = \{ X \in D(x) \mid X[d\omega_i] \equiv 0 \pmod{\omega_1, \ldots, \omega_s} \text{ for } i = 1, \ldots, s \}, \]

$k$-th Derived System $\partial^k D$

\[ \partial^k D = \partial(\partial^{k-1} D) \]

$k$-th Weak Derived System $\partial^{(k)} D$:
Symbol Algebras

$(M, D)$: regular

(S1) \( \exists \mu > 0 \) such that, for all \( k \geq \mu \),
\[
D^{-k} = \cdots = D^{-\mu} \supset D^{-2} \supset D^{-1} = D,
\]

(S2) \([D^p, D^q] \subset D^{p+q}\) for all \( p, q < 0 \).

$(M, D)$: regular such that \( T(M) = D^{-\mu} \).

\[
\forall x \in M,
\]
\[
m(x) = \bigoplus_{\mu=-1}^{\mu} g_p(x).
\]
\[
g_{-1}(x) = D^{-1}(x), g_p(x) = D^p(x)/D^{p+1}(x)
\]
\[
[X, Y] = \omega_{p+q}([\hat{X}, \hat{Y}]_x),
\]
where \( \hat{X} \in \Gamma(D^p), X = \omega_p(\hat{X}_x) \in g_p(x), \hat{Y} \in \Gamma(D^q), Y = \omega_q(\hat{Y}_x) \in g_q(x).
\]
\[
g_p(x) = [g_{p+1}(x), g_{-1}(x)] \quad \text{for} \ p < -1.
\]

Conversely given a

Fundamental Graded Lie Algebra:

\[
m = \bigoplus_{\mu=-1}^{\mu} g_p
\]
i.e., Nilpotent GLA satisfying the generating condition: \( g_p = [g_{p+1}, g_{-1}] \) for \( p < -1 \)

\[\Rightarrow\]

\((M(m), D_m)\): Standard Differential System of type \( m \)

\[\Rightarrow\]
\( g(m) \): Prolongation of \( m = \bigoplus_{p<0} g_p \)

Our Problem:

When does \( g(m) \) become finite dimensional and simple?

Symbol Algebra of \((L(J), E)\):

\[
E = \{\omega = \omega_1 = \cdots = \omega_n = 0\},
\]
\[ c^2(n) = c_{-3} \oplus c_{-2} \oplus c_{-1}, \]

where \( c_{-3} = W, c_{-2} = W \otimes V^* \),

\[ c_{-1} = V \oplus W \otimes S^2(V^*). \]

Coframe:

\[ \{ w, w_i, dx_i, dp_{ij} \}, \quad \{ \frac{\partial}{\partial z}, \frac{\partial}{\partial p_i}, \frac{d}{dx_i}, \frac{\partial}{\partial p_{ij}} \} \]

where

\[ \frac{d}{dx_i} = \frac{\partial}{\partial x_i} + p_i \frac{\partial}{\partial z} + \sum_{j=1}^{n} p_{ij} \frac{\partial}{\partial p_j} \]

\[ \left[ \frac{\partial}{\partial p_{ij}}, \frac{d}{dx_k} \right] = \delta_k^i \frac{\partial}{\partial p_j} + \delta_k^j \frac{\partial}{\partial p_i} \]

\[ \left[ \frac{\partial}{\partial p_i}, \frac{d}{dx_k} \right] = \delta_k^i \frac{\partial}{\partial z}. \]

\[ \partial E = \{ w = 0 \} = \pi_*^{-1} C, \quad Ch(\partial E) = \text{Ker} \pi_* . \]

§3. Differential Systems associated with Simple Graded Lie Algebras.

Gradation of \( \mathfrak{g} \)

\( \mathfrak{g} \): Simple Lie Algebra over \( \mathbb{C} \)

\( \mathfrak{h} \): Cartan Subalgebra \( \Phi \subset \mathfrak{h}^* \): Root System

\( \Delta = \{ \alpha_1, \cdots, \alpha_l \} \): Simple Root System

\[ \mathfrak{g} = \bigoplus_{\alpha \in \Phi^+} \mathfrak{g}_\alpha \oplus \mathfrak{h} \oplus \bigoplus_{\alpha \in \Phi^+} \mathfrak{g}_{-\alpha}. \]

\( \Delta_1 \subset \Delta \): Fix, \( \Phi^+ = \bigcup_{p \geq 0} \Phi^+_p \),

\[ \Phi^+_p = \{ \alpha = \sum_{i=1}^l n_i \alpha_i \mid \sum_{\alpha_i \in \Delta_1} n_i = p \}, \]

\[ \begin{align*}
\mathfrak{g}_p &= \bigoplus_{\alpha \in \Phi^+_p} \mathfrak{g}_\alpha, \quad (p > 0) \\
\mathfrak{g}_0 &= \bigoplus_{\alpha \in \Phi^+_0} \mathfrak{g}_\alpha \oplus \mathfrak{h} \oplus \bigoplus_{\alpha \in \Phi^+_0} \mathfrak{g}_{-\alpha}, \\
\mathfrak{g}_{-p} &= \bigoplus_{\alpha \in \Phi^+_p} \mathfrak{g}_{-\alpha}, \\
\end{align*} \]

Then \( [\mathfrak{g}_p, \mathfrak{g}_q] \subset \mathfrak{g}_{p+q} \) for \( p, q \in \mathbb{Z} \).

Generating Condition: \( m = \bigoplus_{p<0} \mathfrak{g}_p \) \( \star \) \( \mathfrak{g}_p = [\mathfrak{g}_{p+1}, \mathfrak{g}_{-1}] \) for \( p < -1 \)

\[ \Delta_1 \subset \Delta \implies (X_\ell, \Delta_1) : \quad \mathfrak{g} = \bigoplus_{p=-\mu}^\mu \mathfrak{g}_p \]

where \( \mu = \sum_{\alpha_i \in \Delta_1} n_i(\theta), \theta = \sum_{i=1}^l n_i(\theta) \alpha_i \).
Theorem 4.1. $\mathfrak{g} = \bigoplus_{p \in \mathbb{Z}} \mathfrak{g}_p$: Simple Graded Lie Algebra over $\mathbb{C}$ satisfying $(\star)$. 

$X_\ell$: Dynkin Diagram of $\mathfrak{g} \Rightarrow \exists \Delta_1 \subset \Delta$ s.t. $\mathfrak{g} = \bigoplus_{p \in \mathbb{Z}} \mathfrak{g}_p \cong (X_\ell, \Delta_1)$

Classification of $\mathfrak{g} = \bigoplus_{p \in \mathbb{Z}} \mathfrak{g}_p$ with $(\star)$

$(X_\ell, \Delta_1) \Rightarrow M_\mathfrak{g} = G/G'$: R-space $\mu \geq 2 \quad \mathfrak{g}_{-1} \Rightarrow D_\mathfrak{g}$ on $M_\mathfrak{g}$

$(M_\mathfrak{g}, D_\mathfrak{g}) \supset (M_m, D_m)$, $m = \bigoplus_{p < 0} \mathfrak{g}_p$.

Theorem 4.2. $\mathfrak{g} = \bigoplus_{p \in \mathbb{Z}} \mathfrak{g}_p$: Simple Graded Lie Algebra over $\mathbb{C}$ satisfying $(\star)$.

Except for (1), (2), (3),

$\mathfrak{g} = \bigoplus_{p \in \mathbb{Z}} \mathfrak{g}_p \cong \mathfrak{g}(m)$,

where $m = \bigoplus_{p < 0} \mathfrak{g}_p$.

(1) $\mathfrak{g} = \mathfrak{g}_{-1} \oplus \mathfrak{g}_0 \oplus \mathfrak{g}_1$ is of depth 1 ($\mu = 1$).

(2) $\mathfrak{g} = \bigoplus_{p = -2}^{2} \mathfrak{g}_p$ is a contact gradation.

(3) $\mathfrak{g} = \bigoplus_{p \in \mathbb{Z}} \mathfrak{g}_p$ is isomorphic with $(A_\ell, \{\alpha_1, \alpha_i\})$ $(1 < i < \ell)$ $(C_\ell, \{\alpha_1, \alpha_\ell\})$.

Corresponding R-spaces

(1) $\Rightarrow$ Compact Hermitian Symmetric Spaces

(2) $\Rightarrow$ Standard Contact Manifolds

(3) $(A_\ell, \{\alpha_1, \alpha_i\}) \Rightarrow (J(\mathbb{P}^{d}, i - 1), C) (C_\ell, \{\alpha_1, \alpha_\ell\}) \Rightarrow (L(\mathbb{P}^{2\ell - 1}), E)$.


$R \subset L(J)$: submanifold satisfying

$(R.0) \quad p : R \rightarrow J$ ; submersion,

On $L(J)$,

$C^1 = \partial E, \quad C^2 = E$

On $R$,

$D^1 = C^1 |_R, \quad D^2 = C^2 |_R$

$(R; D^1, D^2)$ satisfies:

$(R.1) \quad D^1$: codim. 1, $D^2$: codim. $n + 1$,

$(R.2) \quad \partial D^2 \subset D^1$, 

On $L(J)$,
(R.3) \( Ch(D^1) \subset D^2 \colon \text{codim. } n, \)
(R.4) \( Ch(D^1) \cap Ch(D^2) = \{0\}. \)

**Triplet** \( (R; D^1, D^2) : \text{PD-manifold} \iff (R.1) \sim (R.4) \)

\[ \{0\} = Ch(D^1) \cap Ch(D^2) \subset Ch(D^1) \subset D^2 \subset \partial D^2 \subset D^1 \subset T(R) \]

**Realization Theorem for PD-manifold**

(i) \( (R.1) \text{ and } (R.3) \implies (J, C) \)

\[ J = R/Ch(D^1), \quad D^1 = p_*^{-1}(C), \]
where \( p : R \to J = R/Ch(D^1). \)

(ii) \( (R.1) \text{ and } (R.2) \implies \iota(v) = p_*(D^2(v) \subset C(u) : \text{Legendrian} \)

(iii) \( (R.4) \implies \iota : R \to L(J) : \text{immersion} \)

**Theorem 5.1.**

\( \Phi : (R; D^1, D^2) \to (\hat{R}; \hat{D}^1, \hat{D}^2) : \text{isomorphism} \implies \)

\[ \exists \varphi : (J, C) \to (\hat{J}, \hat{C}) : \text{contact diffeo s.t.}; \]

\[ \begin{array}{ccc}
R & \overset{i}{\longrightarrow} & L(J) \\
\Phi & \downarrow & \downarrow \varphi_* \\
\hat{R} & \overset{i}{\longrightarrow} & L(\hat{J}).
\end{array} \]

**Compatibility Condition** \((C)\)

\( (C) \quad p^{(1)} : R^{(1)} \to R \text{ is onto.} \)

where \( R^{(1)} \): the first prolongation of \( (R; D^1, D^2) \).

**Theorem 5.2.** \( (R : D^1, D^2) : \text{PD-manifold satisfying the condition } (C) \).

\( \forall v \in R : \)

\[ \dim D^1(v) - \dim \partial D^2(v) = \dim Ch(D^2)(v). \]

Especially \( D^1 = \partial D^2 \iff Ch(D^2) = \{0\}. \)

In case rank \( Ch(D^2) > 0, \)

**Geometry of** \( (R; D^1, D^2) \implies \text{Geometry of } (X, D), \)

where \( X = R/Ch(D^2), D^2 = \rho_*^{-1}(D), \rho : R \to X. \)
§5. Single Equations of Goursat Type.

\[ L(J) \supset R = \{ F(x_i, z, p_i, p_{ij}) = 0 \} \]: Hypersurface s.t. \( p : R \to J \); submersion,

\( R \) is of (weak) parabolic type at each \( v \in R \)
\[ \iff \left( \frac{\partial F}{\partial p_{ij}}(v) \right) : \text{rank 1 at each } v \in R \]
\[ \iff (R, D^2) : \text{regular of type } s : \]
\[ s = s_{-3} \oplus s_{-2} \oplus s_{-1}, \]
where \( s_{-3} = \mathbb{R}, s_{-2} = V^*, s_{-1} = V \oplus \{ f \} \subset S^2(V^*), (f)^\perp = \langle e^2 \rangle \subset S^2(V), e \in V. \)
\[ \iff \exists \text{ Coframe } \{ \varpi, \omega_\alpha, \omega_{1\alpha}, \omega_{\alpha\beta} \} (1 \leq \alpha \leq n, 2 \leq \alpha \leq \beta \leq n) \text{ on } R \text{ such that} \]
\[ D^2 = \{ \omega = \omega_1 = \cdots = \omega_n = 0 \}, \]
\[
\begin{align*}
    d\omega & \equiv \omega_1 \land \omega_1 + \cdots + \omega_n \land \omega_n \pmod{\omega}, \\
    d\omega_1 & \equiv \omega_2 \land \omega_1 + \cdots + \omega_n \land \omega_{1n} \pmod{\omega, \omega_1, \cdots, \omega_n}, \\
    d\omega_\alpha & \equiv \omega_1 \land \omega_{1\alpha} + \cdots + \omega_n \land \omega_{n\alpha} \pmod{\omega, \omega_1, \cdots, \omega_n}.
\end{align*}
\]
where \( \omega_{\alpha\beta} = \omega_{\beta\alpha}, \omega_{1\alpha} = \omega_{\alpha1}, 2 \leq \alpha, \beta \leq n. \)

\( R \) is an equation of Goursat type
\[ \iff R ; \text{(weak) parabolic type s.t. } M(E) ; \text{completely integrable,} \]
where \( M(E) \) is the Monge system ;

\[ M(E) = \{ \omega = \omega_1 = \cdots = \omega_n = \omega_\alpha = \omega_{1\alpha} = 0 \ (2 \leq \alpha \leq n) \}. \]

The First Order Covariant System \( N(E) \)

\[ N = N(E) = \{ \omega = \omega_1 = 0 \}. \]

By Two Step Reductions

Geometry of \((R, D^2)\); Goursat Type \( \Rightarrow \) Geometry of \((Y, D_N)\); Type \( c^1(n-1, 2) \),
where \( Y = R/Ch(N), N = \rho_*^{-1}(D_N), \rho : R \to Y. \)
Extended Dynkin Diagrams with the coefficient of the highest root

§6. $G_2$-geometry.

6.1. Standard Contact Manifolds

$\mathfrak{g}$: Simple Lie Algebra over $\mathbb{C}$

$\theta$: Highest Root

$(X_\ell, \Delta_\theta) : \text{Contact Gradation} \quad \Rightarrow \quad \mathfrak{g} = \mathfrak{g}_{-2} \oplus \mathfrak{g}_{-1} \oplus \mathfrak{g}_0 \oplus \mathfrak{g}_1 \oplus \mathfrak{g}_2$

$(J_\theta, C_\theta): \text{Standard Contact Manifolds} \leftarrow \text{Boothby}$
Projectiviation of the (co-)ajoint orbit through the highest root vector

$\Delta_{\theta} \iff \text{Extended Dynkin Diagram}$

6.2. Gradation of $G_2$.

$\forall \alpha_1, \alpha_2 \quad \theta = 3\alpha_1 + 2\alpha_2.$

$\Delta_1 \subset \Delta = \{\alpha_1, \alpha_2\}$

$(G1) \quad \Delta_1 = \{\alpha_1\}. \quad \mu = 3,$

$m = g_{-3} \oplus g_{-2} \oplus g_{-1}$

where $\dim g_{-3} = \dim g_{-1} = 2, \dim g_{-2} = 1.$

$(G2) \quad \Delta_1 = \{\alpha_2\}. \quad \mu = 2$

$m = g_{-2} \oplus g_{-1} : \text{Contact Gradation}$

$(G3) \quad \Delta_1 = \{\alpha_1, \alpha_2\}. \quad \mu = 5,$

$m = g_{-5} \oplus g_{-4} \oplus g_{-3} \oplus g_{-2} \oplus g_{-1}$

where $\dim g_{-1} = 2$ and $\dim g_p = 1$ for others.

Root System $G_2$

$\text{rank} g = \dim \mathfrak{h} = 2$

$\Delta = \{\alpha_1, \alpha_2\}: \text{Simple Root System}$

$\Phi^+$ consists of the following roots

$\alpha_1, \alpha_2,$

$\alpha_2 + \alpha_1, \alpha_2 + 2\alpha_1, \alpha_2 + 3\alpha_1,$

$2\alpha_2 + 3\alpha_1$

Type $G_2$
\((J_\mathfrak{g}, C_\mathfrak{g}): \text{Standard Contact Manifold}\)
\[
\dim J_\mathfrak{g} = 5
\]
\(L(J_\mathfrak{g}): \text{Lagrange-Grassmann Bundle}\)
\[
\dim L(J_\mathfrak{g}) = 8
\]

Orbits Decomposition
\[
L(J_\mathfrak{g}) = O \cup R_1 \cup R_2,
\]

(1) \(O\): Open orbit,

(2) \(R_1\): Codim 1, the Global Model of \((B)\),

(3) \(R_2\): Codim 2, the Global Model of \((A)\).

\(R_2\): compact \(\Rightarrow\) \((G_2, \{\alpha_1, \alpha_2\})\)
\[
X_\ell \not\cong A_\ell \quad \Rightarrow \quad \Delta_\theta = \{\alpha_\theta\}
\]

For Exceptional Simple Lie Algebras, \(\exists_1 \alpha_G: 3 \text{ next to } \alpha_\theta\)

\((X_\ell, \{\alpha_G\}): \mu = 3 \iff (M_\mathfrak{g}, D_\mathfrak{g})\)
\[
\mathfrak{g}_{-3} = W, \quad \mathfrak{g}_{-2} = V, \quad \mathfrak{g}_{-1} = W \otimes V^*. \quad \dim \mathfrak{g}_{-3} = 2
\]
i.e., \((M_\mathfrak{g}, \partial D_\mathfrak{g})\): regular of type \(c^1(r, 2)\).

\[
(J_\mathfrak{g}, C_\mathfrak{g}) \iff (X_\ell, \{\alpha_\theta\})
\]
\[
L(J_\mathfrak{g}) \ni R_2 \quad \Rightarrow \quad (X_\ell, \{\alpha_\theta, \alpha_G\})
\]
\[
L(J_\mathfrak{g}) \ni R_1 \quad \iff \quad (M_\mathfrak{g}, \partial D_\mathfrak{g})
\]
References


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