Jordan algebras and geometry

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Summary

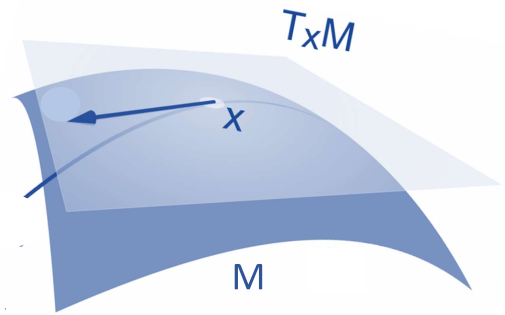


Figure 2. The tangent space TxM at a point x in a symmetric manifold M carries a Jordan algebraic structure

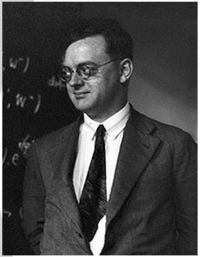
Topics

1. Jordan algebras and symmetric cones
2. Jordan triples and Lie algebras
   (Note: Jordan algebra = Jordan triple + unit)
3. Jordan triples and symmetric manifolds
4. Examples: Spin factors, $H_3(K)$, $K = \mathbb{R}, \mathbb{C}, \mathbb{H}, \mathbb{O}$

Origin of Jordan algebra

P. Jordan, J. von Neumann and E. Wigner,
On an algebraic generalisation of the quantum mechanical formalism,
Ann. of Math. **36** (1934) 29–64.

Von Neumann



Jordan

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An algebra $\mathcal{A}$ (not necessarily associative) (over a field F)

is a *Jordan algebra* if

$$a\,b = b\,a$$

$$a^2(b\,a) = (a^2b)a\,.$$

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$F \;=\; \mathbb{R},\; \mathbb{C}$

Examples

$$H_n(K) = \textit{all } n \times n \textit{ Hermitian matrices over } K, \quad (K = \mathbb{R},\ \mathbb{C},\ \mathbb{H})$$

$$ab := \frac{1}{2}(a.b + b.a) \quad (a.b \textit{ denotes matrix product})$$

K *associative* $\Rightarrow H_n(K)$ is a *special* Jordan algebra.

Let $\mathbb{O}$ $=$ *real Cayley algebra*
$=$ 8 dimensional normed divison algebra over $\mathbb{R}$,
with basis $\{e_0, \ldots, e_7\}$.

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Exceptional Jordan algebras

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Albert algebra $:=$ $H_3(\mathcal{O})$ (over $\mathbb{C}$), $H_3(\mathbb{O})$ (over $\mathbb{R}$)

$=$ all 3×3 Hermitian matrices (a_{ij}) with $a_{ij} \in \mathcal{O}$ (resp. $\mathbb{O}$)
and multiplication

$$(a_{ij})(b_{ij}) = \frac{1}{2}((a_{ij}).(b_{ij}) + (b_{ij}).(a_{ij})).$$

$\mathcal{O}$ is not associative.

spin factor

$H =$ real Hilbert space, inner product $\langle \cdot, \cdot \rangle$

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$H \oplus \mathbb{R}$ is a spin factor, with identity $0 \oplus 1$ and Jordan product

$$(a \oplus \alpha)(b \oplus \beta) := (\beta a + \alpha b) \oplus (\langle a, b \rangle + \alpha\beta).$$

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This is a special real Jordan algebra and $\dim(H \oplus \mathbb{R}) \leq \infty$.

Examples : $\mathbb{R}^n \oplus \mathbb{R}$.

Product of 3 elements = triple product in Jordan algebras

Let A be a Jordan algebra and $a, b, c \in A$. Define

$$\{a, b, c\} = (a\,b)\,c + a\,(b\,c) - b\,(a\,c)$$

which is trilinear.

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$$\{a, b, c\} = \{c, b, a\}$$

$$\{\cdot, \cdot, \cdot\} \quad \text{is}$$

linear in the outer variables; conjugate linear in the middle variable.

Call $\{\cdot, \cdot, \cdot\}$ the canonical triple product of A.

Triple identity

$$\{a, b, \{x, y, z\}\}$$

$$= \{\{a, b, x\}, y, z\} - \{x, \{b, a, y\}, z\} + \{x, y, \{a, b, z\}\}$$

Jordan triples (Meyberg 1970)

A vector space V is a *Jordan triple* if there is a map

$$\{\cdot,\cdot,\cdot\} : V^3 \longrightarrow V,$$

linear in the 1st and 3rd variables, conjugate linear in the 2nd variable, satisfying

(i) $\{a,b,c\} = \{c,b,a\}$

(ii) Triple identity.

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$$\{a, b, c\} = (a\,b^*)c + a\,(b^*c) - b^*(a\,c).$$

e.g. $H_3(\mathcal{O}) = H_3(\mathbb{O}) + iH_3(\mathbb{O})$

left multiplication on Jordan triples

Let V = Jordan triple. Define "left multiplication”, or box operator

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Denote $\Gamma(V) \;:=\;$ Lie group of $V \Box\, V$ = structure group of V.

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$$a^2 + b^2 = 0 \Rightarrow a = b = 0.$$

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- A is a Hilbert space with inner product $\langle a, b \rangle = \mathrm{Trace}\ L_{ab}$

Positive cone of A

A cone Ω in a real vector space is a nonempty set satisfying

(i) $t\Omega \subset \Omega$ for all $t > 0$

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Ω is called proper if $\overline{\Omega} \cap -\overline{\Omega} = \{0\}$.

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$A_+ := \{a^2 : a \in A\}$ is a closed cone in A. Let

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Properties of $\Omega(A)$

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In fact, they characterise formally real Jordan algebras.

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Elie Cartan

Correspondence between A and symmetric cones

Theorem

Let Ω be a proper open cone in a real Hilbert space V ($\dim V < \infty$).
T. F. A. E.

1. $\Omega = \Omega(A)$ *for some formally real Jordan algebra A.*
2. Ω *is linearly homogeneous, self-dual (symmetric cone)*
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$1 \Leftrightarrow 2 \Rightarrow 3$ Koecher and Vinberg (1962/3)

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$1 \Leftrightarrow 3$ Chu, Crelle, 2021. $\square$

Koecher

Vinberg

Examples

A	$H_3(\mathbb{R})$	$H_3(\mathbb{C})$	$H_3(\mathbb{H})$	$H_3(\mathbb{O})$
$\Omega(A)$	$GL(3,\mathbb{R})/O(n)$	$GL(3,\mathbb{C})/U(n)$	$GL(3,\mathbb{H})/Sp(n)$	$E_{6(-26)}/F_4$

Spin factors

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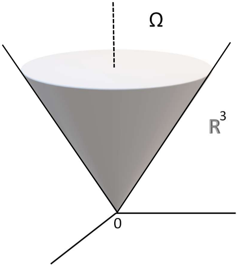
$$\Omega(A) = \{r \oplus a \in \mathbb{R} \oplus \mathbb{R}^n : r > \|a\|_2\}, \quad a = (a_1, \ldots, a_{n-1})$$

$$= \{r \oplus a : r^2 > a_1^2 + \cdots + a_{n-1}^2\} \qquad \text{(Lorentz cone).}$$

Light cone

$$A = \mathbb{R}^2 \oplus \mathbb{R}$$

$$\Omega(A) = \{(x, y, z) \in \mathbb{R}^3 : z^2 > x^2 + y^2\}$$



R³ is a formally real Jordan algebra

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Isaiah Kantor

Jacques Tits

Tits-Kantor-Koecher Lie algebras

A Lie algebra $\mathfrak{g}$ is called 3-graded if $\exists$ 3-grading:

$$\mathfrak{g} = \mathfrak{g}_{-1} \oplus \mathfrak{g}_0 \oplus \mathfrak{g}_1$$

where

$$[\mathfrak{g}_i, \mathfrak{g}_j] \subset \begin{cases} \{0\} & (i + j = \pm 2) \\ \mathfrak{g}_{i+j} & (\textit{otherwise}). \end{cases}$$

A 3-graded Lie algebra $\mathfrak{g}$ is a Tits-Kantor-Koecher Lie algebra (TKK Lie algebra) if

1. $[\mathfrak{g}_{-1}, \mathfrak{g}_1] = \mathfrak{g}_0$,
2. $\exists$ an involution $\theta : \mathfrak{g} \longrightarrow \mathfrak{g}$ such that $\theta(\mathfrak{g}_j) = \mathfrak{g}_{-j}$.

Tits-Kantor-Koecher construction

$\mathcal{V} =$ Category of Jordan triples.

$$\mathcal{G} = \text{ Category of TKK Lie algebras.}$$

Then $\qquad \mathcal{V} \approx \mathcal{G} \qquad$ via

$$\mathfrak{L} : V \in \mathcal{V} \mapsto \mathfrak{L}(V) \in \mathcal{G}.$$

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Then $\mathcal{V} \approx \mathcal{G}$ via

$$\mathfrak{L} : V \in \mathcal{V} \mapsto \mathfrak{L}(V) \in \mathcal{G}.$$

$$\mathfrak{L}(V) := V \oplus (V \square V) \oplus \overline{V} \text{ (conjugate of } V)$$

with involution

$$\theta : x \oplus \sum_j a_j \square b_j \oplus z \in \mathfrak{L}(V) \mapsto z \oplus -\sum_j b_j \square a_j \oplus x \in \mathfrak{L}(V).$$

Example

$V = H_3(\mathcal{O}) \in \mathcal{V} \Rightarrow$

$$\mathfrak{L}(V) = \mathfrak{e}_7 \in \mathcal{G}$$

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Kaup (1977) (1 $-$ 1 *correspondence*)

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Kaup (1977) $\qquad$ (1 − 1 *correspondence*)

A complex normed Jordan triple $(V, \|\cdot\|)$ is Hemitian if

$$a \square a \text{ has } \textit{real} \text{ numerical range}, \ \forall a \in V.$$

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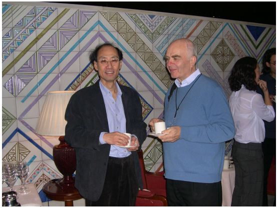

Kaup

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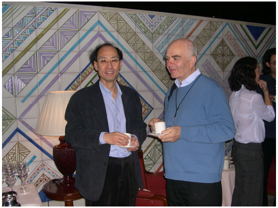

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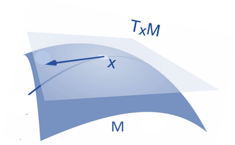

$\Rightarrow$:

Example

Let $V = H_3(\mathcal{O})$, which is Hermitian. Then

$$M = \{(a_{ij}) \in H_3(\mathcal{O}) : \|(a_{ij})\| < 1\} \approx H_3(\mathbb{O}) \oplus i\Omega(H_3(\mathbb{O}))$$

$\uparrow$ Cayley transform

is a Hermitian symmetric manifold and $V \approx T_0 M$.

Jordan theory has developed rapidly in the last three decades, but very few books describe its diverse applications. Here, the author discusses some recent advances of Jordan theory in differential geometry, complex and functional analysis, with the aid of numerous examples and concise historical notes. These include: the connection between Jordan and Lie theory via the Tits-Kantor-Koecher construction of Lie algebras; a Jordan algebraic approach to infinite dimensional symmetric manifolds including Riemannian symmetric spaces; the one-to-one correspondence between bounded symmetric domains and JB*-triples; and applications of Jordan methods in complex function theory. The basic structures and some functional analytic properties of JB*-triples are also discussed
The book is a convenient reference for experts in complex geometry or functional analysis, as well as an introduction to these areas for beginning researchers. The recent applications of Jordan theory discussed in the book should also appeal to algebraists.

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