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GAUGE AND NON-GAUGE CURVATURE TENSOR COPIES

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INTERNATIONAL ATOMIC ENERGY AGENCY

UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION

1982 MIRAMARE-TRIESTE

IC/82/197

International Atomic Energy Agency
and
United Nations Educational Scientific and Cultural Organization

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ABSTRACT

A procedure for constructing curvature tensor copies is discussed using the anholonomic geometrical framework. The corresponding geometries are compared and the notion of gauge copy elucidated. An explicit calculation is also made.

MIRAMARE - TRIESTE
October 1982

* To be submitted for publication.

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I. INTRODUCTION

In gauge theories gauge equivalent potentials are very useful in handling certain problems. In connection with Yang-Mills theory [1], for example, the calculation of topological numbers of the multi-instanton solution can be carried out as an application of the Gauss theorem if we use the 't Hooft solution [2] together with another compact and gauge equivalent solution [3]. For the Abelian case gauge copies were used by Wu and Yang [4] in their formulation of the Dirac monopole [5] theory using overlapping sections into which each monopole divides the space-time. In the non-Abelian case we may also obtain two or more potentials not related by any gauge transformation associated to the same gauge covariant field strength. These field strength copies have been studied in several recent papers [6].

For the case of an affine space-time manifold, likewise, the curvature tensor does not determine the space-time connection uniquely. For example, the projective transformation [7] $\Gamma_{\nu\rho}^{\ \ \mu} \to \Gamma_{\nu\rho}^{\ \ \mu} - \delta^{\mu}_{\nu}\lambda_{\rho}$, $g_{\mu\nu} \to g_{\mu\nu}$ leaves the curvature scale invariant. The importance of eliminating the projective invariance for a consistent theory of gravity interacting with matter was discussed in detail in Ref.7. The curvature tensor is left invariant in the case $\lambda_{\rho} = \partial_{\rho}\chi$. We will discuss in this paper a general procedure to construct curvature tensor copies in analogy to the case of non-Abelian gauge theory. For this purpose we will use the anholonomic geometrical framework (tetrad formulation) which incorporates in it a local (Lorentz) gauge group. The notation is defined in Sec.II. In Sec.III the curvature tensor copies are constructed and the corresponding geometries compared. The notion of gauge copy in the present context is also elucidated. Finally, Sec.IV contains an explicit calculation and describes briefly the procedure to be followed in the case of Weyl-Cartan geometry.

II. NOTATION *): SPINOR CONNECTION

The geometry of the space-time manifold M, labelled by co-ordinates x^{μ}, is described by means of a sufficiently differentiable field of four vectors [8] (tetrad frame), $\underline{e}_{\ell} = e^{\mu}_{\ \ell}\,\partial_{\mu}$, and a linear connection $\underline{\Gamma}$ at each

*) The anholonomic (tetrad or Lorentz) indices $\ell, m, \ldots$ as well as holonomic (co-ordinate or world) indices $\mu, \nu, \ldots$ run from 0 to 3. Also $\eta_{\ell m} = \eta^{\ell m} = \mathrm{diag}(1,-1,-1,-1)$.

point. We also assume the existence of a constant Minkowski metric $\eta_{\ell m}$ and may choose the tetrad to be orthonormal, $\underline{e}_\ell \cdot \underline{e}_m = \eta_{\ell m}$. We have the dual frame $\underline{e}^\ell = e_\mu{}^\ell dx^\mu$ and find $e_\mu{}^\ell e^\mu{}_m = \delta^\ell_m$ which implies $e_\mu{}^\ell e^\nu{}_\ell = \delta^\nu{}_\mu$. Let Γ^ℓ_{mn} be the anholonomic components [9] of the connection $\underline{\Gamma}$ referred to a tetrad basis. We define the mixed components - spinor connection or deformation gauge potential - by

$$\omega_\lambda{}^\ell{}_m = e_\lambda{}^n \Gamma^\ell_{mn} . \qquad (1)$$

and the holonomic components $\Gamma_{\mu\nu}^{\ \lambda}$ of $\underline{\Gamma}$ by [9]

$$\Gamma^\alpha_{\mu\lambda} = e^\alpha{}_\ell \left[\partial_\lambda e_\mu{}^\ell + \omega_\lambda^\ell{}_m e_\mu{}^m \right] . \qquad (2)$$

This implies $\omega_{\lambda m}^{\ \ell} = -e^\mu{}_m (\partial_\lambda e_\mu{}^\ell - \Gamma_{\mu\lambda}^{\ \alpha} e_\alpha{}^\ell)$. A tensor field may be described either by means of its holonomic or its anholonomic components. It is, however, convenient to use also mixed components, e.g. $\phi^{\ell\mu}$, $\phi^{\ell}_{m}{}^{\mu}_{\nu}$, etc. We may also define (complete) covariant derivative *) of such a quantity, for example, as follows:

$$\phi^{\ell\mu}_{m\nu;\lambda} = \partial_\lambda \phi^{\ell\mu}_{m\nu} + \omega_\lambda{}^\ell{}_n \phi^{n\mu}_{m\nu} - \omega_\lambda{}^n{}_m \phi^{\ell\mu}_{n\nu}$$
$$+ \Gamma^\mu_{\alpha\lambda} \phi^{\ell\alpha}_{m\nu} - \Gamma^\alpha_{\nu\lambda} \phi^{\ell\mu}_{m\alpha} \qquad (3)$$

i.e. anholonomic indices are differentiated by means of $\omega_{\lambda m}^{\ \ell}$ and holonomic ones by means of $\Gamma_{\mu\nu}^{\ \lambda}$. Thus Eq.(2) reads $e_\mu{}^\ell{}_{;\lambda} = 0$. The holonomic components of the metric on M are $g_{\mu\nu} = g_{\nu\mu} = e_\mu{}^\ell e_\nu{}^m \eta_{\ell m}$ and **)

$$g_{\mu\nu;\lambda}(\Gamma) = e_\mu{}^\ell e_\nu{}^m \eta_{\ell m;\lambda}(\omega)$$
$$\eta_{\ell m;\lambda}(\omega) = -2\,\omega_{\lambda(\ell m)} \qquad (4)$$

Consider local Lorentz transformations $\Lambda(x) = (\Lambda^\ell{}_m(x))$, i.e. $\eta_{\ell m} \Lambda^\ell{}_p \Lambda^m{}_q = \eta_{pq}$. The rotation of the tetrad at x^μ by $\Lambda(x)$, e.g. $e'_\mu{}^\ell = \Lambda^\ell{}_m e_\mu{}^m$, $e'^\mu{}_\ell = \Lambda_\ell{}^m e^\mu{}_m$ does not affect the metric structure. Since by definition $\phi^\ell{}_{;\lambda}$ transforms as ϕ^ℓ we obtain the transformation rule of the connection $\omega_\lambda = (\omega_\lambda{}^\ell{}_m)$ under Lorentz gauge transformations ($\mathcal{L}$) to be

$$\omega_\mu \xrightarrow{\ \mathcal{L}\ } \Lambda \omega_\mu \Lambda^{-1} - (\partial_\mu \Lambda)\Lambda^{-1} . \qquad (5)$$

The holonomic components $\Gamma_{\mu\nu}^{\ \lambda}$ of $\underline{\Gamma}$ are then seen to be unaltered under tetrad rotations. The geometry of the system is thus invariant under local gauge transformations.

III. CURVATURE TENSOR COPIES. GAUGE COPIES

The space-time curvature tensor is given by

$$R^\mu{}_{\nu\lambda\rho} = \partial_\nu \Gamma^\mu_{\nu\rho} + \Gamma^\mu_{\beta\lambda} \Gamma^\beta_{\nu\rho} - (\lambda \leftrightarrow \rho) . \qquad (6)$$

It is clear from Eq.(5) that, in analogy with the case of Yang-Mills theory, we may define a gauge covariant field strength $P_{\lambda\rho}(\omega)$ - spin curvature tensor - by

$$P_{\lambda\rho}(\omega) = \partial_\lambda \omega_\rho - \partial_\rho \omega_\lambda + [\omega_\lambda, \omega_\rho]$$
$$P_{\lambda\rho}(\omega) \xrightarrow{\ \mathcal{L}\ } \Lambda P_{\lambda\rho}(\omega) \Lambda^{-1} . \qquad (7)$$

The indices in $R^\ell{}_{m\lambda\rho}(\omega) \equiv (P_{\lambda\rho}(\omega))^\ell{}_m$ are all tensorial and it is easy to

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*) The derivative property may be verified even when we do not impose $e_\mu{}^\ell{}_{;\lambda} = 0$. We note that $\delta^\ell_{m;\lambda} = \delta^\nu_{\mu;\lambda} = 0$.

**) For Dirac spinor field $\psi_{;\lambda} = (\partial_\lambda + \Gamma_\lambda)\psi$. Considering transformation of Γ_λ under Lorentz gauge transformations we can show $\Gamma_\mu = \frac{1}{8}[\gamma_\ell, \gamma_m]\,\omega_\mu^{[\ell m]}$. On making use of the identity

$$[\Gamma_\mu, \gamma^\ell] = \frac{1}{2}(\omega_{\mu m}{}^\ell - \omega_\mu{}^\ell{}_m)\gamma^m$$

we find $\gamma^\ell{}_{;\lambda} = \omega_\lambda^{(\ell m)} \gamma_m$. We remark that the definitions above do not impose any symmetry on the indices (ℓ, m) in $\omega_\lambda{}^\ell{}_m$ even when $e_\mu{}^\ell{}_{;\lambda} \neq 0$.

verify using Eq.(2) that *)

$$R^{\alpha}{}_{\mu\lambda\rho}(\Gamma) = e_\mu{}^m e^\alpha{}_\ell R^\ell{}_{m\lambda\rho}(\omega) . \tag{8}$$

The curvature tensor copies arise if we have a connection $\bar{\omega}_\lambda$ such that

$$P_{\lambda\rho}(\bar{\omega}) = P_{\lambda\rho}(\omega) , \tag{9}$$

Writing $\bar{\omega}_\lambda = \omega_\lambda + \kappa_\lambda$ we obtain

$$P_{\lambda\rho}(K) + [\omega_\lambda, K_\rho] - [\omega_\rho, K_\lambda] = 0 . \tag{10}$$

This copy is called a gauge copy if $\bar{\omega}_\lambda$ and ω_λ are connected by a Lorentz gauge transformation, e.g.

$$K_\lambda = -\omega_\lambda + \Lambda\omega_\lambda\Lambda^{-1} - (\partial_\lambda\Lambda)\Lambda^{-1} \tag{11}$$

for some $\Lambda(x)$. On substituting in Eq.(10) this leads to $\Lambda P_{\lambda\rho}(\omega)\Lambda^{-1} = P_{\lambda\rho}(\omega)$.

The holonomic connection $\bar{\Gamma}^\alpha_{\mu\lambda}$ corresponding to $\bar{\omega}_\lambda$ follows to be (Eq.(2))

$$\bar{\Gamma}^\alpha{}_{\mu\lambda} = \Gamma^\alpha{}_{\mu\lambda} + K_\lambda{}^\ell{}_m e_\mu{}^m e^\alpha{}_\ell \tag{12}$$

and

$$g_{\mu\nu;\lambda}(\bar{\Gamma}) = e_\mu{}^\ell e_\nu{}^m \eta_{\ell m;\lambda}(\bar{\omega}) . \tag{13}$$

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*) When $e_\mu{}^\ell{}_{;\lambda} \neq 0$ we use the identity

$$e_\mu{}^\ell{}_{;\lambda\rho}(\Gamma,\omega) - e_\mu{}^\ell{}_{;\rho\lambda}(\Gamma,\omega) + (\Gamma^\alpha_{\lambda\rho} - \Gamma^\alpha_{\rho\lambda})\, e_\mu{}^\ell{}_{;\lambda}(\Gamma,\omega)$$
$$= R^\alpha{}_{\mu\lambda\rho}(\Gamma) e_\alpha{}^\ell - R^\ell{}_{m\lambda\rho}(\omega) e_\mu{}^m$$

The curvature tensor copies may be discussed by setting $e_\mu{}^\ell{}_{;\lambda} = -\kappa_\lambda{}^\ell{}_m e_\mu{}^m$.

The case of curvature scalar copies may also be discussed with appropriate modifications. It is worth pointing out that the last term in Eq.(11) is always antisymmetric and that ω_λ may be decomposed into its irreducible symmetric and antisymmetric components. Thus, if ω_λ is antisymmetric (Einstein-Cartan geometry), a symmetric κ_λ cannot correspond to a gauge copy. A copy with antisymmetric κ_λ corresponds to E.C. geometry.

IV. ILLUSTRATIONS OF SOME CURVATURE TENSOR COPIES

Eq.(10) is similar to that encountered in the study of field strength copies in non-Abelian gauge theory [6]. We will only consider here some simple solutions as illustrations.

An obvious symmetric solution is $\kappa_\lambda = -I(\partial_\lambda\chi)$, $\mathrm{Tr}\,\kappa_\lambda = -4(\partial_\lambda\chi)$ where $\chi(x)$ is a scalar function. We get from Eqs.(12) and (13)

$$\bar{\Gamma}^\alpha{}_{\mu\lambda} = \Gamma^\alpha{}_{\mu\lambda} - \delta^\alpha_\mu \partial_\lambda\chi$$
$$g_{\mu\nu;\lambda}(\bar{\Gamma}) = g_{\mu\nu;\lambda}(\Gamma) + 2 g_{\mu\nu}\partial_\lambda\chi . \tag{14}$$

For $(\partial_\lambda\chi)$ replaced by a vector field φ_λ (projective transformation) we get only a curvature scalar copy [7].

Another simple solution is obtained by making the ansatz

$$K_\lambda = a(x)\,\partial_\lambda\chi , \tag{15}$$

where $a(x) = (a^\ell{}_m(x))$ may correspond to a symmetric or antisymmetric solution. Eq.(10) leads to

$$\partial_\lambda a(x) + [\omega_\lambda, a(x)] = 0 . \tag{16}$$

Consider, for an illustration, the metric space defined by the following line element [10]:

$$ds^2 = dt^2 - 2A(t)\,dz\,dt - C^2(t)(dx^2 + dy^2) \; . \quad (17)$$

We have for the non-vanishing element $g_{00} = 1$, $g_{11} = g_{22} = -C^2$, $g_{03} = g_{30} = -A$, $g^{03} = -A^{-1}$, $g^{11} = g^{22} = -C^{-2}$, $g^{33} = -A^{-2}$ and $\sqrt{-g} = AC^2$. A set of tetrad fields is found with the non-vanishing elements given by

$$e_0^{(0)} = 1 \;,\; e_1^{(1)} = e_2^{(2)} = C \;,\; e_3^{(3)} = e_3^{(0)} = -A \;,$$

$$e^0_{(0)} = -e^0_{(3)} = 1 \;,\; e^3_{(3)} = -A^{-1} \;,\; e^1_{(1)} = e^2_{(2)} = C^{-1} \;, \quad (18)$$

where the indices inside the brackets are the anholonomic indices. We also assume, for definiteness' sake, Γ's to be Christofell connections, $\Gamma_{\mu\nu}^{\ \lambda} = \{{}^{\lambda}_{\mu\nu}\}$. The internal spin connections determined from $e_{\mu\ ;\lambda}^{\ \ell}(\{\}\ \overset{o}{\omega}) = 0$ are antisymmetric and found to be $(\omega_\lambda \equiv \overset{o}{\omega}_\lambda)$

$$\overset{o}{\omega}_3 = 0 \;,\; \overset{o}{\omega}_1 = \dot{C}\begin{pmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & -1 \\ 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix} \;,\; \overset{o}{\omega}_2 = \dot{C}\begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \end{pmatrix} \;,$$

$$\overset{o}{\omega}_0 = \dot{A}A^{-1}\begin{pmatrix} 0 & 0 & 0 & -1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 \end{pmatrix} \;,\quad \overset{o}{\omega}_1\overset{o}{\omega}_2 = \overset{o}{\omega}_2\overset{o}{\omega}_1 = 0 \;. \quad (19)$$

A traceless symmetric solution is found to be $a(t) = A^2M$ where the non-vanishing elements of M are $M^0{}_0 = +M^3{}_0 = -M^0{}_3 = -M^3{}_3 = -1$. Since ω_λ are antisymmetric this cannot correspond to the case of a gauge copy. We find

$$\bar{\Gamma}^{\mu}_{\nu\lambda} = \{{}^{\mu}_{\nu\lambda}\} + A(\partial_\lambda\chi)\,\delta^\mu_3\,\delta^0_\nu$$

$$g_{\mu\nu;\lambda}(\bar{\Gamma}) = 2A^2(\partial_\lambda\chi)\,\delta^0_\mu\,\delta^0_\nu \quad (20)$$

and verify by direct calculation that $R_{\mu\lambda\rho}^{\ \ \ \alpha}(\bar{\Gamma}) = R_{\mu\lambda\rho}^{\ \ \ \alpha}(\Gamma)$.

An antisymmetric solution is found to be $a(t) = (\frac{A}{C})\,\overset{o}{\omega}_1$ and corresponds to

$$\bar{\Gamma}^{\mu}_{\nu\lambda} = \{{}^{\mu}_{\nu\lambda}\} + \left[\frac{A}{C}\,\delta^\mu_1\,\delta^0_\nu - C\,\delta^\mu_3\,\delta^1_\nu\right](\partial_\lambda\chi)$$

$$g_{\mu\nu;\lambda}(\bar{\Gamma}) = 0 \;. \quad (21)$$

However, this case can be shown to correspond to a gauge copy. We find $P_{\lambda\rho} = \left(-\frac{\dot{C}}{C} + \frac{\dot{A}}{A}\right)\left[\delta^0_\rho(\overset{o}{\omega}_1\,\delta^1_\lambda + \overset{o}{\omega}_2\,\delta^2_\lambda) - (\lambda \leftrightarrow \rho)\right]$ so that in order to satisfy $\Lambda P_{\lambda\rho}(\overset{o}{\omega})\,\Lambda^{-1} = P_{\lambda\rho}(\overset{o}{\omega})$ we require $\Lambda\overset{o}{\omega}_{1,2}\,\Lambda^{-1} = \overset{o}{\omega}_{1,2}$ apart from the restrictions that Λ be a Lorentz matrix. Adding to these the restrictions arising from Eq.(11) a tedious calculation shows that the Lorentz gauge matrix $\Lambda(x)$ is given by

$$\Lambda(x) = \begin{pmatrix} 1+\frac{1}{2}\psi^2 & -\psi & 0 & -\frac{1}{2}\psi^2 \\ -\psi & 1 & 0 & \psi \\ 0 & 0 & 1 & 0 \\ \frac{1}{2}\psi^2 & -\psi & 0 & 1-\frac{1}{2}\psi^2 \end{pmatrix} , \quad (22)$$

where $\psi = A(t)\,\chi(x)$.

The case of Weyl-Cartan geometry may also be discussed. The geometry is characterized by $g_{\mu\nu;\lambda}(\Gamma) = 2g_{\mu\nu}\phi_\lambda$ where ϕ_λ is a Weyl field. Since we require $e_{\mu;\lambda}^{\ \ell} = 0$ it follows that $\eta_{\ell m;\lambda}(\omega) = 2\eta_{\ell m}\,\phi_\lambda$, $\omega_{\lambda(\ell m)} = -\eta_{\ell m}\,\phi_\lambda$. We may assume $\omega_\lambda = (\overset{o}{\omega}_\lambda - I\phi_\lambda)$ and $\Gamma_{\mu\nu}^{\ \lambda} = \{{}^{\lambda}_{\mu\nu}\} - \delta^\lambda_\mu\,\phi_\nu$ and proceed along similar lines.

ACKNOWLEDGMENTS

The author would like to thank Professor Abdus Salam, the International Atomic Energy Agency and UNESCO for hospitality at the International Centre for Theoretical Physics, Trieste, where this work was completed. Thanks are also due to Professor P. van Nieuwenhuizen for his comments and for conversations with Professors J. Niederle, J. Tiomno, M. Novello, C.G. de Oliveira and I. Damião Soares. This work has been partially supported by CNPq of Brazil.

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