Title: General Relativity for Cosmology - Lecture 14

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Abstract:

GR for Cosmology, Achim Kempf, Fall 17, Lecture 15

Note Title

Recall: If we choose the bases $\{\frac{\partial}{\partial x^\mu}\}$, $\{dx^\mu\}$, then:

Eg.: $L_{EM} = -\frac{1}{16\pi} F_{\mu\nu}F^{\mu\nu}$

$$S'[g_{\mu\nu},\psi] = \int \left(\frac{1}{16\pi G} R(g_{\mu\nu}(x)) + L_{matter}\,(g_{\mu\nu}(x), \psi^{(i)}(x), \psi^{(i)}_{;\mu}(x))\right)\sqrt{g}\, d^4x$$

$$\frac{\delta S'}{\delta \psi^{(i)}} = 0$$ $\Rightarrow$ Eqns. of motion of matter (Maxwell, Klein Gordon eqns. etc)

$$\frac{\delta S'}{\delta g_{\mu\nu}} = 0$$ $\Rightarrow$ Einstein equation:

e.g. $L_{EM} = \frac{}{16\pi} \ldots_{\mu\nu}$

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$\frac{\delta S'}{\delta \psi^{(i)}} = 0 \quad \Rightarrow$ Eqns. of motion of matter
(Maxwell, Klein Gordon eqns. etc)

$\frac{\delta S'}{\delta g_{\mu\nu}} = 0 \quad \Rightarrow$ Einstein equation:

$$\boxed{R^{\mu\nu} - \frac{1}{2} g^{\mu\nu} R = 8\pi G T^{\mu\nu}}$$

What is the Einstein equation when using a frame so that

$$g_{\mu\nu}(x) = \eta_{\mu\nu} \, ?$$

Recall:

- Frames $\{\theta^\mu\}, \{e_\mu\}$:

Often, one uses as the bases of $T_p(M)$, and $T_p(M)'$ the canonical bases $\{dx^\mu\}$ and $\{\frac{\partial}{\partial x^\mu}\}$ respectively, which suggest themselves when one chooses coordinates, say $(x^0, \ldots, x^3)$. Thus, when changing coordinate system, $x \to \bar{x}$, one also

$$g_{\mu\nu}(x) = \eta_{\mu\nu} \ ?$$

Recall:

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Important: The only reason why the components of a tensor can change when we change coordinates is that we can change basis in the (co-) tangent spaces, namely from one canonical basis to another canonical basis, when we change coord. system.

Recall:

(a fixed vector has different coefficients in different bases:
$\xi^\mu \frac{\partial}{\partial x^\mu} = \xi^\mu \frac{\partial \bar{x}^\nu}{\partial x^\mu} \frac{\partial}{\partial \bar{x}^\nu} = \bar{\xi}^\nu \frac{\partial}{\partial \bar{x}^\nu} \Rightarrow \bar{\xi}^\nu = \frac{\partial \bar{x}^\nu}{\partial x^\mu} \xi^\mu$)

$$\longrightarrow \quad \xi = \xi^\mu \frac{\partial}{\partial x^\mu} = \bar{\xi}^\nu \frac{\partial}{\partial \bar{x}^\nu}$$

We notice: If we choose a fixed basis, say $\{\theta^\mu\}, \{e_\mu\}$ then the coefficients of tensors no longer depend on the choice of coordinates!

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the same numbers in every coordinate system.

E.g.: $\xi = \tilde{\xi}^\mu e_\mu$

Conversely: Even staying with one coordinate system, we can freely change our choice of basis in the (co-)tangent spaces:

scalar functions.

$$\theta'^\mu = A^\mu{}_\nu\, \theta^\nu$$

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$$\theta'^{\mu} = A^{\mu}{}_{\nu}\, \theta^{\nu}$$

$$e'_{\mu} = (A^{-1})_{\mu}{}^{\nu}\, e_{\nu}$$

So we have e.g.:

$$\xi = \xi^{\mu} e_{\mu} = \xi^{\mu} A^{\nu}{}_{\mu}\, e'_{\nu} = \xi'^{\nu} e'_{\nu}$$

I.e.: $\xi'^{\nu} = A^{\nu}{}_{\mu}\, \xi^{\mu}$

Examples:

- The curvature form: $\Omega'^{\mu}{}_{\nu} = A^{\mu}{}_{a} (A^{-1})_{\nu}{}^{b}\, \Omega^{a}{}_{b}$
- But: the connection form $\omega^{\mu}{}_{\nu}(\xi) = \xi^{k}\, \Gamma^{\mu}_{k\nu}$ obeys:

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$$\omega'^{\mu}{}_{\nu} = A^{\mu}{}_{a}\, \omega^{a}{}_{b} (A^{-1})_{\nu}{}^{b} - (dA)^{\mu}{}_{c} (A^{-1})_{\nu}{}^{c}$$

How to specify frames?

In an arbitrary coordinate system, we may specify the bases in terms of the canonical bases:

$$\theta^i(x) = A^i{}_j(x)\, dx^j$$

(Another possibility? Take n scalar functions $f^{(1)}, \dots, f^{(n)}$ and define $\theta^i := df^{(i)}$. For generic functions these $\{\theta^i\}$ will be linearly independent almost everywhere)

Note: the $A^i{}_j(x)$ change nontrivially when changing the coordinate system!

Our choice now: orthonormal frames, or "Tetrads":

□ We say that a frame $\{\theta^r\}, \{e_r\}$ is orthonormal if in this frame, for all $p \in M$:

Our choice now: orthonormal frames, or "Tetrads":

- We say that a frame $\{\theta^\mu\},\{e_\mu\}$ is orthonormal if in this frame, for all $p\in M$:

$$g(e_\mu,e_\nu) = \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix}_{\mu,\nu} = \eta_{\mu\nu} \quad \text{i.e. if:} \quad g = -\theta^0\otimes\theta^0 + \sum_{i=1}^{3}\theta^i\otimes\theta^i$$

- Existence? Always: At each $p\in M$ may choose e.g. $\theta^\mu = dx^\mu$ where dx^μ are canonical ON basis at centre of a geodesic cds.

- Uniqueness?

Uniqueness?

For a given space-time, $(\mathcal{M}, g)$, any ON frame yields a new ON frame by transforming the bases through

$$\theta'^{\mu}(x) = \Lambda(x)^{\mu}{}_{\nu}\, \theta^{\nu}(x),$$

if the linear maps $\Lambda(x)$ preserve the orthonormality:

$$\eta_{\mu\nu}\, \theta'^{\mu} \otimes \theta'^{\nu} = \eta_{ab}\, \theta^{a} \otimes \theta^{b}$$

recall: this is the defining equation for Lorentz transformations.

i.e. if: $\Lambda^{\mu}{}_{a} \Lambda^{\nu}{}_{b}\, \eta_{\mu\nu} = \eta_{ab}$ (*)

$\Rightarrow$ Frames are unique up to local Lorentz transformations.

Re-express the degrees of freedom:

- We used to specify space-times through these data: $(\mathcal{M}, g)$
- Now, let us specify space-times, equivalently, through data $(\mathcal{M}, \{\theta^\mu\})$:

Namely:

Assume the $\{\theta^\mu\}$ are given w. resp. to a basis $\{dx^\mu\}$, through functions $A^\mu{}_\nu$,

$$\theta^\mu(x) = A^\mu{}_\nu(x)\, dx^\nu$$

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$$\theta^\mu(x) = A^\mu{}_\nu(x)\, dx^\nu$$

so that: $g_{\mu\nu} = \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix} = \eta_{\mu\nu}$ in the basis $\{\theta^i\}$!

Notice: knowing the $A^\mu{}_\nu(x)$, we can reconstruct $g_{\mu\nu}(x)$ in basis $\{dx^\mu\}$:

We use that the abstract g is the same in every basis:

$$g = \underbrace{\eta_{\mu\nu}\,\theta^\mu \otimes \theta^\nu}_{\text{because it's tetrad}} = \overbrace{\eta_{\mu\nu} A^\mu{}_a A^\nu{}_b}^{= g_{ab}(x)}\, dx^a \otimes dx^b = g_{\mu\nu}(x)\, dx^\mu \otimes dx^\nu$$

$$\Longrightarrow \quad \boxed{g_{ab}(x) = \eta_{\mu\nu} A^\mu{}_a(x) A^\nu{}_b(x)}$$

$\Longrightarrow$ $\{\theta^i(x)\}$ indeed determines $g_{\mu\nu}(x)$:

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$$\Rightarrow \quad \boxed{g_{ab}(x) = \eta_{\mu\nu} A^\mu{}_a(x) A^\nu{}_b(x)}$$

$\Rightarrow$ $\{\theta^i(x)\}$ indeed determines $g_{\mu\nu}(x)$:

$\Rightarrow$ The $A^\mu{}_\nu(x)$ carry all physical (here shape) info!

How then does $A^{\sim}{}_{\nu}(x)$ encode $C^i_{jk}, \omega^i_j, \Omega^i_j$?

Start with orthonormal frame: $\boxed{\theta^i(x) = A^i_j(x)\, dx^j}$ (*)

1.) How do the $A^i_j(x)$ determine the $C^i_{jk}(x)$?

Recall from lecture 11:

$$d\theta^i(x) = -\frac{1}{2} C^i_{jk}(x)\, \theta^j(x) \wedge \theta^k(x)$$

Here: $d\theta^i(x) = A^i_{j,k}(x)\, dx^k \wedge dx^j$ because of (*)

$$= -\frac{1}{2} C^i_{ab}\, \theta^a \wedge \theta^b = -\frac{1}{2} C^i_{ab} A^a_k A^b_j\, dx^k \wedge dx^j$$

$\Longrightarrow \quad A^i_{j,k} = -\frac{1}{2} C^i_{ab} A^a_k A^b_j$

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1.) How do the $A^i{}_j(x)$ determine the $C^i{}_{jk}(x)$?

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$$\Rightarrow \quad A^i{}_{j,k} = -\frac{1}{2} C^i{}_{ab} A^a{}_k A^b{}_j$$

$$\Rightarrow \quad \boxed{C^i{}_{ab}(x) = -2 A^i{}_{j,k}(x) \left(A^{-1}(x)\right)^j{}_k \left(A^{-1}(x)\right)^k{}_b}$$

$$\Rightarrow \boxed{C^i_{ab}(x) = -2\, A^i_{\ j,k}(x)\, \left(A^{-1}(x)\right)^j_{\ a} \left(A^{-1}(x)\right)^k_{\ b}}$$

2.) The $C^i_{jk}(x)$ yield the $\Gamma^i_{jk}(x)$ through:

$$\Gamma^l_{ki} := \frac{1}{2}\left(C^l_{ki} - g_{is}\, g^{lj} C^s_{kj} - g_{ks}\, g^{lj} C^s_{ij}\right)$$ (lecture 11)

$$+\frac{1}{2}\, g^{lj}\left(\cancel{g_{ij,k} + g_{jk,i} - g_{ki,j}}\right)$$ ← These all vanish because $g_{\mu\nu,\sigma} = 0$ now

Notice: This simplifies for orthonormal frames with $g_{\mu\nu}(x) = \eta_{\mu\nu}$!

3.) The $\Gamma^i_{kj}(x)$ yield the $\omega^i_j(x)$:

$$\omega^i_{\ j}(x) := \Gamma^i_{kj}(x)\, \theta^k(x)$$

(lecture 11)

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3.) The $\Gamma^i{}_{kj}(x)$ yield the $\omega^i{}_j(x)$:

$$\omega^i{}_j(x) := \Gamma^i{}_{kj}(x)\, \theta^k(x)$$

4.) Recall the 2nd structure equation:

$$\Omega^i{}_j(x) := d\omega^i{}_j + \omega^i{}_k \wedge \omega^k{}_j$$

$\Rightarrow$ We have: $A^i{}_j \to \theta^i \to C^i{}_{jk} \to \Gamma^i{}_{jk} \to \omega^i{}_j \to \Omega^i{}_j$

Recall important identities: (torsionless case)

- Structure eqn. I:

$$\Theta^i = D\theta^i = d\theta^i + \omega^i{}_j \wedge \theta^j = 0$$

(Ordinarily: $\theta^i = dx^i \Rightarrow d\theta^i = 0$ and $\omega^i{}_j \wedge \theta^j = 0$ is $\Gamma^i_{jk} = \Gamma^i_{kj}$)

- Structure eqn II:

$$\Omega^i{}_j = d\omega^i{}_j + \omega^i{}_k \wedge \omega^k{}_j$$

(Recall: $R^{\cdot}{}_{\cdots} = \Gamma^{\cdot}_{\cdot\cdot,\cdot} + \Gamma^{\cdot}_{\cdot\cdot,\cdot} + \Gamma^{\cdot}_{\cdot\cdot}\Gamma^{\cdot}_{\cdot\cdot} + \Gamma^{\cdot}_{\cdot\cdot}\Gamma^{\cdot}_{\cdot\cdot}$)

- Bianchi identity I:

$$\Omega^i{}_j \wedge \theta^j = 0$$

- Bianchi identity II: (From diffeomorphism invariance)

$$D\Omega^i{}_j = 0$$

And, in the case of ON frames:

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And, in the case of ON frames:

$$\omega_{\mu\nu} + \omega_{\nu\mu} = 0$$

Tetrad formulation of GR:

Consider the action, for now, without cosmological constant and without matter:

$$S_{grav} := \frac{1}{16\pi G} \int_B \overset{\text{0-form}}{R} \sqrt{g}\, d^4x$$

Recall Hodge $*$: If $\quad v = \frac{1}{p!} v_{i_1 \dots i_p} \theta^{i_1} \wedge \dots \wedge \theta^{i_p}$

then $\quad *v = \frac{1}{p!} \sqrt{g}\, \overset{= \pm 1,\ \text{totally anti-symmetric}}{\varepsilon_{i_1 \dots i_n}} v^{i_1 \dots i_p} \theta^{i_{p+1}} \wedge \dots \wedge \theta^{i_n}$

i.e. $\quad * : \Lambda^p \to \Lambda^{n-p}$

Thus:

$$S = \frac{1}{\dots} \int *R$$

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i.e. $\quad * : \Lambda^p \rightarrow \Lambda^{n-p}$

Thus:

$$S'_{grav} = \frac{1}{16\pi G} \int_B \underbrace{*R}_{\text{4-form}}$$

Aim now: Re-express $S'_{\mu\nu}$ in terms of θ^μ and $\Omega^\mu{}_\nu$.

□ Define:

"capital η" is a $(0,2)$ tensor-valued 2-form

$$H_{\alpha\beta} := *(\theta^\alpha \wedge \theta^\beta) = \frac{1}{2}\overset{\overset{1}{\shortparallel}}{\sqrt{g}}\,\varepsilon_{\alpha\beta\gamma\delta}\,\theta^\gamma \wedge \theta^\delta$$

$$H_{\alpha\beta\gamma} := *(\theta^\alpha \wedge \theta^\beta \wedge \theta^\gamma) = \frac{1}{2}\overset{\overset{1}{\shortparallel}}{\sqrt{g}}\,\varepsilon_{\alpha\beta\gamma\delta}\,\theta^\delta$$

a $(0,3)$ tensor-valued 1-form.

□ Proposition:

$$*R = H_{\mu\nu} \wedge \Omega^{\mu\nu}$$

(it is a $(0,0)$ tensor-valued 4-form)

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Proposition:

$$*R = H_{\mu\nu} \wedge \Omega^{\mu\nu}$$

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i.e.: $$\boxed{S_{grav}(\theta^\mu) = \int H_{\mu\nu} \wedge \Omega^{\mu\nu}}$$

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Proof:

Use $\Omega^\mu{}_\nu = \frac{1}{2} R^\mu{}_{\nu\kappa\lambda}\, \theta^\kappa \wedge \theta^\lambda \Longrightarrow$

$$H_{\mu\nu} \wedge \Omega^{\mu\nu} = \frac{1}{2\cdot 2}\, \varepsilon_{\mu\nu\gamma\delta}\, R^{\mu\nu}{}_{\kappa\lambda}\, \underbrace{\theta^\gamma \wedge \theta^\delta \wedge \theta^\kappa \wedge \theta^\lambda}_{= \varepsilon_{\gamma\delta\kappa\lambda}\, \theta^\gamma \otimes \theta^\delta \otimes \theta^\kappa \otimes \theta^\lambda}$$

Use also: $\varepsilon_{\mu\nu\gamma\delta}\, \varepsilon_{\gamma\delta\kappa\lambda} = 2\left(\delta_{\kappa\mu}\delta_{\lambda\nu} - \delta_{\kappa\nu}\delta_{\lambda\mu}\right) \Longrightarrow$

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Use $\Omega^{\mu}{}_{\nu} = \frac{1}{2} R^{\mu}{}_{\nu\kappa\lambda} \theta^{\kappa} \wedge \theta^{\lambda} \implies$

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Use also: $\varepsilon_{\mu\nu\gamma\delta} \varepsilon_{\gamma\delta\kappa\lambda} = 2(\delta_{\kappa\mu}\delta_{\lambda\nu} - \delta_{\kappa\nu}\delta_{\lambda\mu}) \implies$

$$H_{\mu\nu} \wedge \Omega^{\mu\nu} = \frac{4}{4} R^{\mu\nu}{}_{\mu\nu} \, \theta^1 \wedge \theta^2 \wedge \theta^3 \wedge \theta^4 = *R \checkmark$$

(need later for derivation of the Einstein equation)

Proposition: $D H_{\mu\nu} = 0$

Recall the "first structure equation": $D\theta^{\mu} = 0$

constant because ON basis

Use $\Omega^{\mu}{}_{\nu} = \frac{1}{2} R^{\mu}{}_{\nu\kappa\lambda}\, \theta^{\kappa} \wedge \theta^{\lambda} \Longrightarrow$

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Use also: $\varepsilon_{\mu\nu\gamma\delta}\, \varepsilon_{\gamma\delta\kappa\lambda} = 2\left(\delta_{\kappa\mu}\delta_{\lambda\nu} - \delta_{\kappa\nu}\delta_{\lambda\mu}\right) \Longrightarrow$

(need later for derivation of the Einstein equation) $\rightarrow$

$$H_{\mu\nu} \wedge \Omega^{\mu\nu} = \frac{4}{4} R^{\mu\nu}{}_{\mu\nu}\, \theta^{1} \wedge \theta^{2} \wedge \theta^{3} \wedge \theta^{4} = \ast R \;\checkmark$$

- **Proposition:** $DH_{\mu\nu} = 0$

Recall the "first structure equation": $D\theta^{\mu} = 0$

- **Proof:** $DH_{\mu\nu} = D\Big(\overbrace{\tfrac{1}{2} \underset{=1}{\sqrt{g}}\, \varepsilon_{\mu\nu\varsigma\sigma}}^{\text{constant because ON basis}}\, \theta^{\varsigma} \wedge \theta^{\sigma}\Big) = \frac{1}{2}\, \varepsilon_{\mu\nu\varsigma\sigma}\Big(\underbrace{D\theta^{\varsigma}}_{=0} \wedge \theta^{\sigma} + \theta^{\varsigma} \wedge \underbrace{D\theta^{\sigma}}_{=0}\Big)$

The main proposition:

variation, not co-derivative

Variation of the action with respect to $\underbrace{\delta\Theta^\mu(x)}_{''}$ yields:

i.e., we vary the $A^\mu{}_\nu(x)$ by local Lorentz transformations

$$\delta(*R) = (\delta\Theta^\mu) \wedge H_{\mu\nu\rho} \wedge \Omega^{\nu\rho} + d(\text{something})$$

Stokes: $\int_B df = \int_{\partial B} f$

It implies:

$$16\pi G\, \delta S_{grav} = \int_B \delta\Theta^\mu \wedge H_{\mu\nu\rho} \wedge \Omega^{\nu\rho} + \int_{\partial B} (\text{something})$$

← require variation to vanish at boundary ∂B, so: $= 0$

Definition: The "energy-momentum 1-form" T_μ is defined as the solution to:

$$\delta S_{\mu} =: \int \delta\Theta^\mu \wedge (*T_\mu)$$

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$$16\pi G\, \delta S_{grav} = \int_B \delta\theta^\mu \wedge H_{\mu\nu\xi} \wedge \Omega^{\nu\xi} + \int_{\partial B} (\text{something})$$

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Definition: The "energy-momentum 1-form" T_μ is defined as the solution to:

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⇒ The equation of motion, i.e., the Einstein equation,

$$\frac{\delta(S'_{grav} + S'_{matter})}{\delta\theta^\mu} = 0$$

becomes:

$$\boxed{-\frac{1}{2} H_{\mu\nu\rho} \wedge \Omega^{\nu\rho} = 8\pi G \, *T_\mu}$$

$$16\pi G\, \delta S'_{grav} = \int_B \delta\theta^\mu \wedge H_{\mu\nu g} \wedge \Omega^{\nu g} + \int_{\partial B} (\text{something})$$

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$$\boxed{-\frac{1}{2} H_{\mu\nu\rho} \wedge \Omega^{\nu\rho} = 8\pi G \, {*T_\mu}}$$

<u>Exercise:</u> add the cosmological constant.

(it is a (0,1) tensor-valued 1 form)

<u>Remark:</u> The Einstein form $G_\mu := G_{\mu\nu}\,\theta^\nu$ obeys

$$*G_\mu = -\frac{1}{2} H_{\mu\nu\rho} \wedge \Omega^{\nu\rho}$$

$$\frac{\delta(S'_{grav} + S'_{matter})}{\delta\theta^\mu} = 0$$

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$$*G_\mu = -\frac{1}{2} H_{\mu\nu\rho} \wedge \Omega^{\nu\rho}$$

$$\Rightarrow \quad \boxed{G_\mu = 8\pi G\, T_\mu}$$

Proof of the main proposition:

$$\delta(*R) = (\delta\theta^\mu) \wedge H_{\mu\nu\rho} \wedge \Omega^{\nu\rho} + d(\text{something})$$

Indeed:

$$\delta(*R) = (\delta H_{\mu\nu}) \wedge \Omega^{\mu\nu} + H_{\mu\nu} \wedge \delta\Omega^{\mu\nu}$$

Consider the first term:

$$\delta H_{\mu\nu} = \delta\, \overbrace{\tfrac{1}{2}\sqrt{g}\,\varepsilon_{\mu\nu\rho\sigma}}^{\text{const.}}\, \theta^\rho \wedge \theta^\sigma$$

$$= (\delta\theta^\rho) \wedge H_{\mu\nu\rho}$$

by definition of $H_{\mu\nu\rho}$ above: $H_{\mu\nu\rho} := \frac{1}{2}\sqrt{g}\,\varepsilon_{\alpha\beta\gamma\delta}\,\theta^\delta$

$$\Rightarrow \quad \delta(*R) = (\delta\theta^\mu) \wedge H_{\mu\nu\rho} \wedge \Omega^{\nu\rho} + \underbrace{H_{\mu\nu} \wedge \delta\Omega^{\mu\nu}}$$

Indeed:

$$\delta(*R) = (\delta H_{\mu\nu}) \wedge \Omega^{\mu\nu} + H_{\mu\nu} \wedge \delta\Omega^{\mu\nu}$$

Consider the first term:

$$\delta H_{\mu\nu} = \delta \overbrace{\tfrac{1}{2}\sqrt{g}\,\varepsilon_{\mu\nu\rho\sigma}}^{\text{const.}} \theta^\rho \wedge \theta^\sigma$$

$$= (\delta\theta^\rho) \wedge H_{\mu\nu\rho}$$

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2nd structure equation

$$\Rightarrow \quad \delta(*R) = (\delta\theta^{\mu}) \wedge H_{\mu\nu\rho} \wedge \Omega^{\nu\rho} + \underbrace{H_{\mu\nu} \wedge \delta\Omega^{\mu\nu}}_{\text{examine this term:}}$$

$$\delta\Omega^{\mu\nu} \overset{\text{2nd structure equation}}{=} \delta(d\omega^{\mu\nu} + \omega^{\mu}{}_{\rho} \wedge \omega^{\rho\nu})$$

$$= d\delta\omega^{\mu\nu} + (\delta\omega^{\mu}{}_{\rho}) \wedge \omega^{\rho\nu} + \omega^{\mu}{}_{\rho} \wedge \delta\omega^{\rho\nu}$$

$$\Rightarrow \quad H_{\mu\nu} \wedge \delta\Omega^{\mu\nu} = d(H_{\mu\nu} \wedge \delta\omega^{\mu\nu}) - (dH_{\mu\nu}) \wedge \delta\omega^{\mu\nu}$$

$$+ H_{\mu\nu} \wedge \delta\omega^{\mu}{}_{\rho} \wedge \omega^{\rho\nu} + H_{\mu\nu} \wedge \omega^{\mu}{}_{\rho} \wedge \delta\omega^{\rho\nu}$$

$$\overset{\text{by Def. of } D:}{=} (\delta\omega^{\mu\nu}) \wedge DH_{\mu\nu} + d(H_{\mu\nu} \wedge \delta\omega^{\mu\nu})$$

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$$\overset{\text{by Def. of } D:}{=} (\delta\omega^{\mu\nu})\wedge \underbrace{DH_{\mu\nu}}_{\substack{\text{recall: } =0 \\ \text{by Prop. above.}}} + d(H_{\mu\nu}\wedge\delta\omega^{\mu\nu})$$

$\Rightarrow$ Indeed:

$$\delta(*R) = (\delta\theta^{\mu})\wedge H_{\mu\nu\rho}\wedge\Omega^{\nu\rho} + d(H_{\mu\nu}\wedge\delta\omega^{\mu\nu}) \quad ✓$$

General Relativity as a "gauge theory"

Recall:

$$S_{grav}(\theta^\mu) = \int H_{\mu\nu} \wedge \Omega^{\mu\nu} \qquad \text{Einstein action}$$

$$-\frac{1}{2} H_{\mu\nu\rho} \wedge \Omega^{\nu\rho} = 8\pi G \, {*T_\mu} \qquad \text{Einstein equation}$$

are now the same in all coordinate systems.

In addition:

They are the same also with any choice of ON bases in the tangent spaces, i.e., we have a local symmetry under:

$$\theta^\mu(x) \longrightarrow \tilde{\theta}^\mu(x) = A^\mu{}_\nu(x)\, \theta^\nu(x)$$

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The $A^\mu{}_\nu(x)$ are local Lorentz transformations.

Upshot: We can start with any matter theory that is invariant under global Lorentz transformations and, through general relativity, turn it into a theory that is invariant under local Lorentz transformations.

Thereby:

Derivatives become covariant derivatives.

A new field is introduced: gravity's Γ.

⇝ This is analogous to the gauge principle of particle physics:

A global symmetry is "gauged" to become local.

The gauge principle:

Action for a Dirac field (electrons, quarks etc):

$$S[\psi] = \int \bar{\psi}\left(i\gamma^\mu \partial_\mu - m\right)\psi \, d^4x$$

It has a global symmetry:

$$\psi(x) \to \tilde{\psi}(x) := e^{i\alpha}\psi(x), \text{ i.e., } \bar{\psi}(x) \to \bar{\tilde{\psi}}(x) = e^{-i\alpha}\bar{\psi}(x)$$

$$\Rightarrow S[\psi] \to S[\tilde{\psi}] = S[\psi]$$

However, no local symmetry:

$$\psi(x) \to \tilde{\psi}(x) := e^{i\alpha(x)}\psi(x) \qquad \bar{\psi}(x) \to \bar{\tilde{\psi}}(x) = e^{-i\alpha(x)}\bar{\psi}(x)$$

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$$S[\Psi] \to S[\tilde{\Psi}] \neq S[\Psi] \; !$$

Gauge principle: Introduce a new field $A_\mu(x)$ that transforms so as to absorb the extra term:

$$S'[\psi, A] := \int \bar{\psi}(x)\Big(i\gamma^\mu \underbrace{(\partial_\mu + iA_\mu(x))}_{\text{"covariant derivative"}} - m\Big)\,\psi(x)\, d^4x$$

Now under

$$\psi(x) \to \tilde{\psi}(x) := e^{i\alpha(x)}\psi(x)$$

$$A_\mu(x) \to \tilde{A}_\mu(x) := A_\mu(x) - i\,\partial_\mu \alpha(x)$$

the action obeys:

$$S[\psi, A] \longrightarrow S'[\tilde{\psi}, \tilde{A}]$$

$$= \int \bar{\psi}(x)\, e^{-i\alpha(x)}\Big(i\gamma^\mu(\partial_\mu + iA_\mu - i\partial_\mu\alpha - m\Big)e^{i\alpha(x)}\psi(x)\, d^4x$$

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$$= S[\psi, A]$$

Generalization to Yang-Mills theory

Gauging $\psi(x) \to e^{i\alpha(x)}\psi(x)$ introduced $A_\mu(x)$.

and $A_\mu(x)$ turns out to exist: The EM 4-potential.

We "derived" the electromagnetic force!

Notice: $e^{i\alpha(x)} \in \mathcal{U}(1)$

$$\mathcal{U}(1) = \{ G \in \mathbb{C} \mid G^+ = G^{-1} \}$$

Now give the Dirac particles an extra index (isospin bundle)

$$S'[\psi] = \int \overline{\psi}_a \left(i\gamma^\mu \delta_{ab} \partial_\mu - m\delta_{ab} \right) \psi_b \, d^4x \qquad \left(\sum_{a,b} \text{implied} \right)$$

It's invariant under:

$$\psi_a(x) \to G_{ab}\psi_b(x) \qquad \left(\sum_{b=1}^{N} \text{implied} \right)$$

where $G \in SU(N)$

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$$SU(N) = \{ G \in M_n(\mathbb{C}) \mid G^+ = G^{-1}, \det(G) = 1 \}$$

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⇝ Invariance of the action now requires new field $B_\mu(x)$:

$$S'[\psi] = \int \bar{\psi}_a \left(i\gamma^\mu \underbrace{\left(\delta_{ab}\partial_\mu + i\, B_\mu(x)_r T^r_{ab} \right)}_{\text{"covariant derivative"}} - m\delta_{ab} \right) \psi_b \, d^4x$$

and $B_\mu(x)_r \to \tilde{B}_\mu(x)_r = B_\mu(x)_r + \text{complicated}$

Here: $T^r_{ab} \in su(N)$ are a Lie algebra basis, i.e. they are generators of infinitesimal $SU(N)$ transformations.

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Upshot:
- $N=2$ Weak force (though mixed with $N=1$ EM)
- $N=3$ Strong force QCD.

Recall:

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$$\theta^\mu(x) \longrightarrow \tilde{\theta}^\mu(x) = A^\mu{}_\nu(x)\, \theta^\nu(x)$$

The $A^\mu{}_\nu(x)$ are **local Lorentz transformations**.

Our covariant derivative:

$$\nabla_{e_\mu} \left(V^\nu(x)\, e_\nu\right) = \left(\frac{\partial}{\partial x^\mu} V^\nu(x)\right) e_\nu + V^\nu(x)\, \omega^\rho{}_\nu(e_\mu)\, e_\rho$$

$$\theta^\mu(x) \longrightarrow \tilde{\theta}^\mu(x) = \Lambda^\mu{}_\nu(x)\,\theta^\nu(x)$$

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Do the $\omega^\rho{}_\nu$ indeed generate infinitesimal Lorentz transformations?

Plays rôle of A_μ, B_μ but is now gravity!

→ Interpretation of the connection in ON frames:

Q: The connection 1-forms $\omega^\mu{}_\nu$ are not, we know, tensor-valued 1-forms. Wherein do they take their values?

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Q: The connection 1-forms $\omega^\mu{}_\nu$ are not, we know, tensor-valued 1-forms. Wherein do they take their values?

A: The connection 1-forms take values in the set of infinitesimal Lorentz transformations

Intuition?

The connection yields the change under infinitesimal parallel transport - and parallel transport preserves the metric, i.e. it preserves the lengths of vectors, i.e. the change can only be an infinitesimal "rotation", i.e. an infinitesimal Lorentz transformation.

Recall: "Lorentz transformations $\Lambda^\mu{}_a$" are lin. maps obeying:

$$\Lambda^\mu{}_a \Lambda^\nu{}_b \eta_{\mu\nu} = \eta_{ab}$$

$\Rightarrow$ Infinitesimal Lorentz transformations

$$\Lambda^\mu{}_a = \delta^\mu{}_a + \varepsilon^\mu{}_a \qquad \text{with } (\varepsilon^\mu{}_a)^2 = 0$$

obey:

$$(\delta^\mu{}_a + \varepsilon^\mu{}_a)(\delta^\nu{}_b + \varepsilon^\nu{}_b)\eta_{\mu\nu} = \eta_{ab}$$

i.e.: $\varepsilon^\mu{}_a \eta_{\mu b} + \varepsilon^\nu{}_b \eta_{a\nu} = 0$

$\Rightarrow$ Infinitesimal Lorentz transformations "ILT" are given by

all $\Lambda^\mu{}_a = \delta^\mu{}_a + \varepsilon^\mu{}_a$ which obey: $\boxed{\varepsilon_{ba} + \varepsilon_{ab} = 0}$

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Q: Are connection 1-forms JLT-valued?

Proposition:

In orthonormal frames, the 1-form $\omega_{\mu\nu}$ obeys

$$\omega_{\mu\nu} + \omega_{\nu\mu} = 0$$

i.e. it takes values that are infinitesimal Lorentz transformations.

Proof:

Recall: Absolute exterior derivative: (an anti-derivation)

$$Dt^{a..b}{}_{c..d} = dt^{a..b}{}_{c..d} + \omega^a{}_i \wedge t^{i..b}{}_{c..d} + \ldots - \omega^i{}_c \wedge t^{a..b}{}_{i..d} - \ldots$$

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any tensor-valued differential form.

play the rôle of the $\Gamma^{a}{}_{bc}$

Thus:

(0,2) tensor-valued 0 form

$= 0$ because $g_{\mu\nu} = \eta_{\mu\nu} = \text{const}$

can drop the $\wedge$ because g is a 0-form.

$$0 = \nabla g_{\mu\nu} = Dg_{\mu\nu} = dg_{\mu\nu} - \omega^{i}{}_{\mu} \wedge g_{i\nu} - \omega^{i}{}_{\nu} \wedge g_{\mu i}$$

Recall that by using a tetrad, we achieved that $g_{\mu\nu} = \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix} = \eta_{\mu\nu}$

$$\omega_{\mu\nu} + \omega_{\nu\mu} = 0$$

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Recall that by using a tetrad, we achieved that $g_{\mu\nu} = \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix} = \eta_{\mu\nu}$ everywhere!

i.e. $0 = \omega_{\nu\mu} + \omega_{\mu\nu}$ ✓