Moscow International School of Physics 2022

Canonical description for formulation of embedding gravity as General Relativity with additional matter

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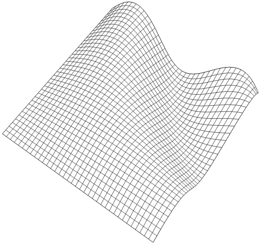
28 July 2022

Embedding theory and Regge-Teitelboim equations

Embedding theory: approach to describe gravity.



- embedding function $y^a(x^\mu) : \mathcal{M} \to \mathbb{R}^{N_+,N_-}$
- $\mu = 0, 1, 2, 3 \qquad a = 0, 1, \ldots, N-1$
- ambient space metric η_{ab} is flat
- surface metric $g_{\mu\nu}$ is induced: $g_{\mu\nu} = (\partial_\mu y^a)(\partial_\nu y^b)\eta_{ab}$

Einstein-Hilbert action: $S = \int d^4x \sqrt{-g}(\frac{R}{2\varkappa} + \mathcal{L}_m)$

Independent variable: $g_{\mu\nu}$ (OTO) $\to$ $y^a(x)$ (embedding theory)

Equations of motion (Regge-Teitelboim equations): $D_\mu\Big((G^{\mu\nu} - \varkappa T^{\mu\nu})\partial_\nu y^a\Big) = 0$

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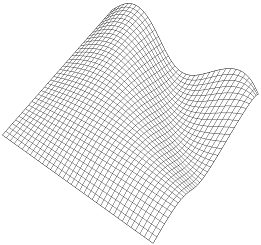

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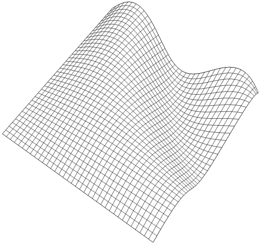

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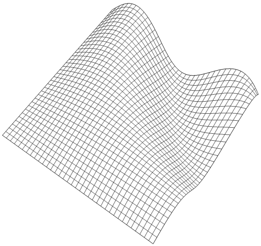

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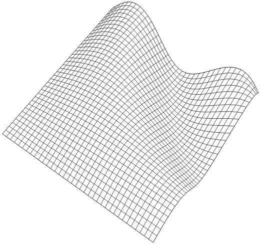

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Regge-Teitelboim equations

We introduce the notation $\varkappa\tau^{\mu\nu} = (G^{\mu\nu} - \varkappa T^{\mu\nu})$, then

- Einstein equations with the contribution of some additional (fictitious) matter with the energy-momentum tensor $\tau^{\mu\nu}$::

$$G^{\mu\nu} - \varkappa(T^{\mu\nu} + \tau^{\mu\nu}) = 0;$$

- The embedding matter equation of motion:

$$D_\mu\big(\tau^{\mu\nu}\partial_\nu y^a\big) = 0.$$

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Reformulating the embedding theory as GR with embedding matter at the level of action

The equivalence between embedding theory and GR with fictitious embedding matter at the level of equations of motion:

$$D_\mu\Big((G^{\mu\nu} - \varkappa T^{\mu\nu})\partial_\nu y^a\Big) = 0 \Leftrightarrow \begin{array}{l} G^{\mu\nu} - \varkappa(T^{\mu\nu} + \tau^{\mu\nu}) = 0 \\ D_\mu\big(\tau^{\mu\nu}\partial_\nu y^a\big) = 0 \end{array}$$

The same equivalence at the level of action:

$$S[y^a] = \frac{1}{2\varkappa}\int d^4x\sqrt{-g}R \Leftrightarrow \begin{array}{l} S = S^{\mathrm{EH}} + S_{\mathrm{m}} + S^{\mathrm{add}} \\ S^{\mathrm{add}} = ? \end{array}$$

$$S^{\mathrm{add}} = \frac{1}{2}\int d^4x\sqrt{-g}\Big(g_{\mu\nu} - (\partial_\mu y^a)(\partial_\nu y_a)\Big)\tau^{\mu\nu}$$

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Change of variables

Arnowitt-Deser-Mizner variables (ADM):

$$\beta_{ik} = g_{ik}, \qquad N_k = g_{0k}, \qquad N = \frac{1}{\sqrt{-g^{00}}}.$$

The ADM action:

$$S^{\mathrm{ADM}} = \int d^4x \Big(2NK_{ik}L^{ik,lm}K_{lm} + \frac{1}{2\varkappa} N\sqrt{\beta}\,\overset{3}{R} \Big).$$

Notation:

$$K_{ik} = \frac{1}{2N}\Big(\overset{3}{D}_i N_k + \overset{3}{D}_k N_i - \partial_0 \beta_{ik} \Big);$$

$$L^{ik,lm} = \frac{\sqrt{\beta}}{8\varkappa}\Big(\beta^{il}\beta^{km} + \beta^{im}\beta^{kl} - 2\beta^{ik}\beta^{lm} \Big);$$

$$\overline{L}_{ik,lm} = \frac{2\varkappa}{\sqrt{\beta}}\Big(\beta_{il}\beta_{km} + \beta_{im}\beta_{kl} - \beta_{ik}\beta_{lm} \Big).$$

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Change of variables

From $\tau^{\mu\nu}$ to ϕ, ϕ^k, ϕ^{ij}:

$$\phi = -\frac{1}{2}N^2\sqrt{\beta}\tau^{00};$$
$$\phi^k = -N\sqrt{\beta}\tau^{k0} - \frac{\phi}{N}(N^k + \beta^{ik}e_i^b e_{b0});$$
$$\phi^{ij} = -\frac{1}{2}N\sqrt{\beta}\tau^{ij} + \beta^{ik}\overline{\beta}^{jm}\frac{\phi}{N}e_k^a e_m^b e_{0a}e_{0b}.$$

Notation:

$$e_\mu^a = \partial_\mu y^a;$$
$$\overline{\beta}_{ik} = e_i^a e_{ak}.$$

$$S^{\text{add}} = \int d^4x\left((\overline{\beta}_{ij} - \beta_{ij})\phi^{ij} + (e_i^a e_{a0} - N_i)\phi^i + \left(N + \frac{1}{N}e_{a0}\overset{3}{\Pi}{}_{\perp}^{ab}e_{b0}\right)\phi\right),$$

Here $\overset{3}{\Pi}{}_{\perp}{}^{a}_{b} = \delta^a_b - e_i^a e_{bj}\overline{\beta}^{ij}$.

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Momenta, primary constraints

Momenta corresponding to the ADM variables β_{ik}, N_k, N:

$$\pi^{ik} = \frac{\delta S}{\delta \dot{\beta}_{ik}} = -2L^{ik,lm}K_{lm}, \qquad \pi_N^k = 0, \qquad \pi_N = 0.$$

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Hamiltonian

$$\mathcal{H} = \pi^{ik}\dot{\beta}_{ik} + p_a\dot{y}^a - \mathcal{L} + \text{primary constraints with Lagrange multipliers}$$

Hamiltonian density $\mathcal{H}$ can be conveniently broken down into two terms

$$\mathcal{H} = \mathcal{H}^{\mathrm{ADM}} + \mathcal{H}^{\mathrm{add}},$$

where

$$\mathcal{H}^{\mathrm{ADM}} = \frac{1}{2}N\pi^{ik}\overline{L}_{ik,lm}\pi^{lm} + \pi^{ik}\left(\overset{3}{D}_i N_k + \overset{3}{D}_k N_i\right) - \frac{1}{2\varkappa}N\sqrt{\beta}\overset{3}{R} + \lambda\Phi + \lambda_k\Phi^k,$$

$$\mathcal{H}^{\mathrm{add}} = \frac{N}{4\phi}p_a\overset{3}{\Pi}{}^{ab}_{\perp}p_b + \phi^{ij}(\beta_{ij} - \overline{\beta}_{ij}) + p_a e^a_i\overline{\beta}^{ik}N_k - \phi N + \chi\Psi + \chi^i\Psi_i + \chi^{ij}\Psi_{ij} + \xi^i\Omega_i.$$

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Secondary constraints

All the primary constraints T_α, $\alpha = 1 \dots M$ must be preserved: $\dot{T}_\alpha = \{H, T_\alpha\} \approx 0$.

Conditions for the conservation of primary constraints give the first generation of secondary constraints:

$$\Xi = \phi + \frac{\zeta}{2} p_\perp \approx 0;$$
$$\mathcal{H}_0 = \mathcal{H}_0^{\mathrm{ADM}} + \zeta p_\perp \approx 0;$$
$$\mathcal{H}_k = \mathcal{H}_k^{\mathrm{ADM}} + e_k^a p_a \approx 0;$$
$$\Sigma_{ij} = \beta_{ij} - \overline{\beta}_{ij} \approx 0.$$

Next generation of secondary constraints:

$$\Lambda_{ik} = \overline{L}_{ik,lm} \pi^{lm} - 2\zeta n_a \overset{3}{b}{}^a_{ik} \approx 0;$$

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Notation:

$$\mathcal{H}_0^{\mathrm{ADM}} = \frac{1}{2} \pi^{ik} \overline{L}_{ik,lm} \pi^{lm} - \frac{1}{2\varkappa} \sqrt{\beta} \overset{3}{R};$$

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$$p_\perp = \sqrt{-p_a \overset{3}{\Pi}{}^{ab}_\perp p_b};$$
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$$p_\perp^a = \overset{3}{\Pi}{}^{ab}_\perp p_b;$$
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Conditions for the conservation of primary constraints give the first generation of secondary constraints:

$$\Xi = \phi + \frac{\zeta}{2} p_\perp \approx 0;$$
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Hamiltonian density as a linear combination of the constraints

It is convenient to write the Hamiltonian density as a linear combination of the constraints already introduced:

$$\mathcal{H} = N\mathcal{H}_0 + N^k\mathcal{H}_k + \Sigma_{ij}\big(\phi^{ij} + \beta^{ik}\overline{\beta}^{jm} e^a_k p_a N_m\big) + \lambda\Phi + \lambda_k\Phi^k + \chi\Psi + \chi^i\Psi_i + \chi^{ij}\Psi_{ij} + \xi^i\Omega_i.$$

First and second class constraints

First class constraints

First class constraints are constraints whose Poisson brackets with all other constraints are just constraints linear combinations:

$$\{T_\alpha, T_\beta\} = C^\gamma_{\alpha\beta} T_\gamma \approx 0.$$

Quantizing the theory with first class constraints T_α, $\alpha = 1 \dots M$:

$$[\widehat{T}_\alpha, \widehat{T}_\beta] = \widehat{C}^\gamma_{\alpha\beta} \widehat{T}_\gamma;$$

$$\widehat{T}_\alpha \, |\varphi\rangle = 0.$$

This does not work with second class constraints!

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variables:

y^a	p_a
β_{ik}	π^{ik}

Hamiltonian:

$$\mathcal{H} = \widetilde{N}\mathcal{H}_0 + \widetilde{N}^k\mathcal{H}_k + \Sigma_{ij}\left(\phi^{ij} + \beta^{ik}\overline{\beta}^{jm} e_k^a p_a N_m\right).$$

Two options:

- Eliminate the embedding function y^a and its conjugate momentum p_a.
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Solving the remaining second class constraints

Solution:

$$\beta_{ij} = \overline{\beta}_{ij}; \qquad \pi^{ij} = 2\zeta n_a b^a_{lk} L^{lk,ij}.$$

First order action:

$$S^{(1)} = \int dt \int d^3x \Big(\pi^{ik} \dot{\beta}_{ik} + p_a \dot{y}^a - N\mathcal{H}_0 - N^k \mathcal{H}_k \Big).$$

Then

$$\boxed{\mathcal{L}^{(1)} = -\zeta \Big(B_{ab} n^b + \frac{1}{2} (n_c B^{cb} n_b + B^c_c) n_a \Big) \dot{y}^a - N\mathcal{H}_0 - N^k \mathcal{H}_k,}$$

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Secondary constraints:

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Hamiltonian after solving the constraints:

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Conclusions

For the complete embedding theory formulated in the form of GR with an additional contribution of the so-called *embedding matter*, the canonical description of the theory is constructed.

- All the constraints are found.
- Some of the constraints are second class.
- Second class constraints are solved by eliminating the variables β_{ik}, π^{ik}.
- The constructed canonical system passes into the canonical formulation of the complete embedding theory.

Next steps:

- Solving the constraints by excluding canonical variables in such a way that the variables β_{ik}, π^{ik}, as well as variables describing embedding matter remain.
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