Chern-Simons Gravity induces Conformal Gravity

QGSC VI

Danilo Diaz and me

September 12, 2013
Motivation

1.  3d Chern Simons Conformal gravity
2.  3d Chern Simons AdS gravity

Chern Simons is a Conformal Gravity

Comments and outlooks

Danilo Diaz and me

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Conformal Gravity

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Conformal Gravity

Four dimensional Conformal Gravity

\[ \int \left( W_{\mu\nu\alpha\beta} W_{\mu\nu\alpha\beta} \right) \sqrt{g} dx^4 \]
Conformal Gravity is interesting

- It has been mentioned
  - It was considered as a possible UV completion of gravity.
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- It was also useful for constructing supergravity theories.
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- It was considered as a possible UV completion of gravity.
- It was also useful for constructing supergravity theories.
- It has recently emerged from the twistor string theory.
- It can have a rôle in AdS/CFT.
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Chern Simons Gravity

2n + 1-dimensional transgression form

\[ I_{2n+1} = (n + 1) \int_{\mathcal{M}} \int_0^1 dt \left\langle (A_1 - A_0) \wedge F_t \wedge \ldots \wedge F_t \right\rangle, \quad (1) \]

where \( A_1 \) and \( A_0 \) are two (1-form) connections in the same fiber.

\( F_t = dA_t + A_t \wedge A_t \) with \( A_t = tA_1 + (1 - t)A_0 \). \( \langle \rangle \) stands for the trace in the group.

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The (Euler) Chern Simons density

Provided $A_0 = 0$ one gets Chern Simons action for $A_1$, or vice versa, in $d = 2n + 1$. 
The (Euler) Chern Simons density

Provided $A_0 = 0$ one gets Chern Simons action for $A_1$, or vice versa, in $d = 2n + 1$.

The Chern Simons equation of motion

$$\langle F^n \delta A \rangle = 0$$

where $F = dA + A \wedge A$. 
Chern Simons gauge theories are interesting

They are gauge theories

- different from YM
Chern Simons gauge theories are interesting

They are gauge theories

- different from YM
- in a sense purely topological
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Chern Simons gauge theories are interesting

They are gauge theories
- different from YM
- in a sense purely topological
- connected with gravitational theories in a non trivial or standard way
Chern Simons gauge theories are interesting

- different from YM
- in a sense purely topological
- connected with gravitational theories in a non trivial or standard way
- full of surprises.
Rewritten as 1.5 formalism

In 3 dimensions conformal gravity

$$I_{CG} = \int_M w_i \wedge dw^i + \frac{2}{3} \varepsilon^{ijk} w_i \wedge w_j \wedge w_k \quad (2)$$

where $w_i = \varepsilon_{ijk} \omega^{kl}_{\mu} dx^\mu$ is the Levi Civita (spin) connection associated a given dreibein $e^i_{\mu} dx^\mu$. 
The equations of motion

\[ C_{\mu\nu\lambda} = \nabla_\mu \rho_{\nu\lambda} - \nabla_\lambda \rho_{\nu\mu} = 0, \]  

(3)
equivalent to the vanishing of the Cotton-York tensor. Here

\[ \rho_{\mu\nu} = R_{\mu\nu} - \frac{1}{4} R g_{\mu\nu}, \]  

(4)
with \( \rho_{\mu\nu} \) is sometimes called the Schouten tensor or plainly \( \rho \)-tensor.
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This means

the solution must a conformally flat space.
Rewritten as a gauge theory

This action principle $d = 3$

The previous action can be written in terms of a connection for conformal group in 3 dimensions ($\text{CFT}_3 \approx \text{SO}(3,2)$)

$$A_\mu = e^i_\mu P_i + w^i_\mu J_i + \lambda^i_\mu K_i + \phi_\mu D.$$  

(5)
Written as a gauge theory

Provided

\[ T^i = de^i + \omega^i_j e^j = 0 \]
\[ \lambda^i_\mu dx^\mu = -\frac{1}{2} R^i_\mu dx^\mu = \rho^i \]
\[ D\rho^i = 0 \]
\[ \phi_\mu = 0 \]

The previous equations of motion can be rewritten as
\[ F = dA + A \wedge A = 0. \]
Written as a gauge theory

Provided

\[
T^i = de^i + \omega^i_j e^j = 0
\]
\[
\lambda^i_\mu dx^\mu = -\frac{1}{2} R^i_\mu dx^\mu = \rho^i
\]
\[
D\rho^i = 0
\]
\[
\phi_\mu = 0
\]

The previous equations of motion can be rewritten as
\[F = dA + A \wedge A = 0.\] This is equivalent to require a conformally flat space.
Chern Simons on-shell

No surprise

The conformal gravity action can be written as 3d Chern Simons action

\[ I_{CS} = \frac{k}{8\pi} \int_M \left( A \wedge dA + \frac{2}{3} A \wedge A \wedge A \right) \]  \hspace{1cm} (6)

for the conformal group.
The Tractor Connection arises

**Conformal connection**

In mathematical lore the connection for $SO(3,2) \approx CFT_3$

$$A = e^i P_i + w^i J_i + \rho^i K_i$$

is called the Tractor Connection.
The Tractor Connection arises

Conformal connection

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is called the Tractor Connection. Recall this is partially on-shell.
Weyl Transformations

Weyl as Conformal

A Weyl transformation, $g_{ij} \rightarrow e^{2\xi} g_{ij}$, of $A$ is

$$A \rightarrow e^{\xi(x)D} A e^{-\xi(x)D} + e^{\xi(x)D} d(e^{-\xi(x)D})$$

where $\xi(x)$ is an arbitrary function of the coordinates of the base space $\{x^\mu\}$. 
Weyl Transformations

Weyl in components

The component of $A$ transforms as

\[
\begin{align*}
e^i & \rightarrow e^\xi e^i \\
\omega^{ij} & \rightarrow \omega^{ij} + \gamma^i e^j - \gamma^j e^i \\
\rho^i & \rightarrow e^{-\xi}(\rho^i + D\gamma^i + \gamma^i \gamma_\mu dx^\mu + e^i \gamma_\mu \gamma^\mu)
\end{align*}
\]

with $\gamma_\mu = \partial_\mu \xi(x)$ and $\gamma^i = E^{i\mu} \gamma_\mu = E^{i\mu} \partial_\mu \xi(x)$
A theory of AdS gravity in $d = 3$

A Chern Simons theory for $\text{AdS}_3 \approx \text{SO}(2, 2)$ written in terms of

$$A = \frac{1}{2} \omega^{AB} J_{AB}$$

where $J_{AB}$ ($A, B = 1 \ldots 4$) are the generator by
A theory of AdS gravity in $d = 3$

A Chern Simons theory for $\text{AdS}_3 \approx \text{SO}(2, 2)$ written in terms of $A = \frac{1}{2} \omega^{AB} J_{AB}$ where $J_{AB}$ ($A, B = 1 \ldots 4$) are the generator by splitting

$$A = \frac{1}{2} \hat{\omega}^{AB} J_{AB} = \frac{1}{2} \hat{\omega}^{ij} J_{ij} + \hat{q}^i J_{i4},$$

where $i, j = 1, 2, 3$. 
A theory of AdS gravity in $d = 3$

A Chern Simons theory for $\text{AdS}_3 \approx \text{SO}(2, 2)$ written in terms of $A = \frac{1}{2} \omega^{AB} J_{AB}$ where $J_{AB}$ ($A, B = 1 \ldots 4$) are the generator by splitting

$$A = \frac{1}{2} \hat{\omega}^{AB} J_{AB} = \frac{1}{2} \hat{\omega}^{ij} J_{ij} + \hat{q}^i J_{i4},$$

(7)

where $i, j = 1, 2, 3$.

2. Next, identifying $\hat{q}^i$ and $\hat{\omega}^{ij}$ with $\hat{q}^i = l^{-1} e^i$, where $e^i$ is a dreibein and $\hat{\omega}^{ij} = \omega^{ij}$ a Lorentz (spin) connection on the manifold to be considered.
How to take the trace

This is not a minor issue and most relevant results can be extracted from the analysis of the different traces.
How to take the trace

This is not a minor issue and most relevant results can be extracted from the analysis of the different traces. Nonetheless the trace can be defined as

\[ \langle J_{A_1} A_2 J_{A_3} A_4 \rangle = \varepsilon_{A_1 \ldots A_4}, \]

which splits, throughout \( A = (i, 4) \) with \( i = 1 \ldots 3 \), as

\[ \varepsilon_{A_1 \ldots A_4} = \varepsilon_{i_1 i_2 i_3 4} = \varepsilon_{i_1 i_2 i_3}. \]
Rewritten action

Chern Simons action can be written as

\[ I_{CS}^3 = l^{-1} \int \left( R^{ij} e^k + \frac{1}{3l^2} e^i e^j e^k \right) \varepsilon_{ijk} + BT \]

where \( R^{ij} = d\omega^{ij} + \omega^i_k \omega^{kl} \) is called the curvature two form.

This is rather standard

This action is actually Einstein (Cartan) gravity in three dimensions.
Equation of Motion are

\[ F = 0 \text{ means} \]

\[
\begin{align*}
F^{ij} &= R^{ij} + \frac{1}{l^2} e^i \wedge e^j = 0 \\
F^{i4} &= T^i = de^i + \omega^i_k e^k = 0
\end{align*}
\]
Equation of Motion are

\[ F = 0 \text{ means} \]

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Solution

This allows only torsion free constant curvature manifolds
Equation of Motion are

\[ F = 0 \text{ means} \]

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F^{ij} = R^{ij} + l^{-2} e^i \wedge e^j = 0
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\[
F^{i4} = T^i = de^i + \omega^i{}_k e^k = 0
\]

Solution

This allows only torsion free constant curvature manifolds, \( i.e., \) \( AdS_3/\Gamma \) with \( \Gamma \in AdS_3 \).
We had one theory for two groups

Conformal

Provided $\mathcal{G} = CFT_3 = SO(3, 2)$ $F = 0$ implies conformal gravity and spaces conformally flat.
We had one theory for two groups

**Conformal**

Provided $G = CFT_3 \simeq SO(3, 2)$ $F = 0$ implies conformal gravity and spaces conformally flat.

**AdS**

Provided $G = AdS_3 \simeq SO(2, 2)$ $F = 0$ implies standard gravity and spaces locally AdS.
We had one theory for two groups

**Conformal**

Provided $\mathcal{G} = CFT_3 = SO(3,2)$ $F = 0$ implies conformal gravity and spaces conformally flat.

**AdS**

Provided $\mathcal{G} = AdS_3 = SO(2,2)$ $F = 0$ implies standard gravity and spaces locally AdS.

**Conformal is AdS somehow**

It is quite appealing to try to connect both.
The previous can be generalized

A SO(2n,2) connection

Given \( A = \frac{1}{2} \omega^{AB} J_{AB} \), where \( J_{AB} \) are the generator of SO(2n,2)

\[
A = \frac{1}{2} \hat{\omega}^{AB} J_{AB} = \frac{1}{2} \hat{\omega}^{ab} J_{ab} + \hat{q}^a J_{a2n+2},
\]

(8)

where \( a, b = 1 \ldots 2n + 1 \).
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A SO(2n,2) connection

Given $A = \frac{1}{2} \omega^{AB} J_{AB}$, where $J_{AB}$ are the generator of SO(2n,2)

$$A = \frac{1}{2} \hat{\omega}^{AB} J_{AB} = \frac{1}{2} \hat{\omega}^{ab} J_{ab} + \hat{q}^a J_{a,2n+2}, \quad (8)$$

where $a, b = 1 \ldots 2n + 1$.

Traces

$$\langle J_{A_1 A_2} \cdots J_{A_{2n+1} A_{2n+2}} \rangle = \varepsilon_{A_1 \cdots A_{2n+2}} = \varepsilon_{a_1 \cdots a_{2n+1} 2n+2},$$

This is the trace considered for the rest of this work.
A more useful Chern Simons action

AdS-Chern-Simons gravity, module a boundary term, can be rewritten in the form of a Lovelock gravity as

$$\int \sum_{p=0}^{n} \frac{1}{2n-2p} \binom{n}{p} \varepsilon_{a_1 \ldots a_{2n+1}} R^{a_1 a_2} \ldots R^{a_{2p-1} a_{2p}} q^{a_{2p+1}} \ldots q^{a_{2n+1}}$$

(9)

where $q^a = \omega^{a_{2n+1}}$ and $R^{ab} = d\omega^{ab} + \omega^a \omega^c \omega^{cb}$ with $a, b, c = 1, \ldots, 2n + 1$. 
More complex equations of motion

The new concept

En 2+1 dimensions $F = 0$ is a simple equation of motion, in higher odd dimensions this complicates. For instance in 5 the equation of motion is

$$F \wedge F = 0$$

or for SO(4,2)
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En 2+1 dimensions $F = 0$ is a simple equation of motion, in higher odd dimensions this complicates. For instance in 5 the equation of motion is

$$F \wedge F = 0$$

or for SO(4,2)

$$\mathcal{E}_f = \varepsilon_{abcdf} (R^{ab} + q^a \wedge q^b) \wedge (R^{cd} + q^c \wedge q^d) = 0$$

$$\mathcal{E}_{df} = \varepsilon_{abcdf} (R^{ab} + q^a \wedge q^b) \wedge (dq^c + \omega^c_e \wedge q^e) = 0$$
A tractor like connection

AdS group in $d$ dimensions

\[
[J_{AB}, J_{CD}] = -\delta_{AB}^{EF} \delta_{CD}^{GH} \eta_{EG} J_{FH},
\]

with $A, B = 0 \ldots d + 1$. 

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A tractor like connection

AdS group in $d$ dimensions

$$[J_{AB}, J_{CD}] = -\delta^{EF}_{AB} \delta^{GH}_{CD} \eta_{EG} J_{FH},$$  \hspace{1cm} (10)

with $A, B = 0 \ldots d + 1$.

Conformal Group in $d - 1$ dimensions

$$[M_{ij}, M_{kl}] = -\delta^{mn}_{ij} \delta^{op}_{kl} \eta_{mo} M_{np}$$

$$[M_{ij}, P_k] = - (\eta_{ik} P_j - \eta_{jk} P_i)$$

$$[M_{ij}, K_k] = - (\eta_{ik} K_j - \eta_{jk} K_i)$$

$$[P_i, K_j] = 2M_{ij} - 2\eta_{ij} D$$

$$[D, P_i] = P_i$$

$$[D, K_i] = -K_i$$

$$[D, M_{ij}] = 0$$

with $i, j = 0 \ldots d - 1$. 
The most provocative relation ever

\[ J_{ij} = M_{ij}, \quad J_{id-1} = \frac{1}{2}(P_i + K_i), \quad J_{d-1d} = D, \quad J_{id} = \frac{1}{2}(P_i - K_i). \] (12)
Generalization

The $d$-dimensional tractor connection is

$$ A = \frac{1}{2} \omega^{ij} J_{ij} + e^i P_i + \rho^i K_i \quad (13) $$

where $\omega^{ij}$ and $e^i$ are a spin connection and a vielbein on the manifold considered.
AdS tractor connection

Generalization

The $d$-dimensional tractor connection is

$$A = \frac{1}{2} \omega^{ij} J_{ij} + e^i P_i + \rho^i K_i$$  \hspace{1cm} (13)

where $\omega^{ij}$ and $e^i$ are a spin connection and a vielbein on the manifold considered. On the other hand,

$$\rho^i = e^i_{\nu} \rho^{\nu}_{\mu} dx^\mu$$

with $\rho^{\mu}_{\nu}$ is given by

$$\rho^{\nu}_{\mu} = \frac{1}{d - 3} \left( R^{\nu}_{\mu} - \frac{1}{2(d - 2)} \delta^{\nu}_{\mu} R \right)$$  \hspace{1cm} (14)
Some algebra

\[ A = \frac{1}{2} \omega^{ij} J_{ij} + \rho^i (J_{id-1} + J_{id}) + e^i (J_{id} - J_{id-1}) \]

\[ = \frac{1}{2} \omega^{ij} J_{ij} + (e^i - \rho^i)J_{id} + (e^i + \rho^i)J_{id-1} \]  

(15)
Conformal Gravity from Chern Simons

Add a dimension and wrap it

The idea is to show that a conformal theory of gravity can be written as a Chern Simons gauge theory with the help of an extension of tractor connection mentioned above.
Add a dimension and wrap it

The idea is to show that a conformal theory of gravity can be written as a Chern Simons gauge theory with the help of an extension of tractor connection mentioned above.

This is not direct

A tractor connection for SO\((d - 1, 2)\) exist on a \(d - 1\) dimensions manifold while a SO\((d - 1, 2)\)-CS density exist in \(d = 2n + 1\) dimensions.
Solution proposed

Dimensional reduction of a 2n+1-CS density on $\mathcal{M}' = \mathcal{M} \times S^1$ to produce an effective 2n-dimensional theory.
AdS tractor connection

The generalization

On space $\mathcal{M}' = \mathcal{M} \times S^1$

$$A_{2n+1} = \frac{1}{2} \omega^{ij}(x^\mu) J_{ij} + e^i(x^\mu) P_i + \rho^i(x^\mu) K_i + \Phi(x^\mu) d\varphi D$$

where $i, j = 1, 2, \ldots 2n$ and a system of coordinates $X^M = (x^\mu, \varphi)$ has been considered on $\mathcal{M}'$ with $\varphi$ parametrizing $S^1$. 
This is sound

The presence of $\Phi d\varphi$ along $D$ does not change the law of transformation under Weyl transformations. Furthermore $\Phi d\varphi$ transforms as

$$\Phi d\varphi \rightarrow \Phi d\varphi - d\xi.$$ 

This transformation has no effect on the CS action due to $d\xi$ has only projection on $\mathcal{M}$. 
The presence of $\Phi d\varphi$ along $D$ does not change the law of transformation under Weyl transformations. Furthermore $\Phi d\varphi$ transforms as

$$\Phi d\varphi \rightarrow \Phi d\varphi - d\xi.$$ 

This transformation has no effect on the CS action due to $d\xi$ has only projection on $\mathcal{M}$. This defines that $\Phi$ is actually a scalar field under Weyl transformations.
A simple example is 3d to 2d

This leads to the identification

\[ \hat{\omega}^{ij} = \omega^{ij} \]
\[ \hat{\omega}^{i3} = \rho^{i} + e^{i}, \]
\[ \hat{\omega}^{34} = \Phi(x) d\varphi = q^{3}, \]
\[ \hat{\omega}^{i4} = e^{i} - \rho^{i} = q^{i}, \]

This yields to the splitting of the three dimensional \( R^{ab} \) as

\[ \hat{R}^{ij} = R^{ij} - (\rho^{i} + e^{i})(\rho^{j} + e^{j}) \]
\[ \hat{R}^{i3} = D(\rho^{i} - e^{i}), \quad (16) \]
Finally the CS action given by

\[ l_3 = \int_{\mathcal{M}'} \varepsilon_{abc} \left( \hat{R}^{ab} q^c + \frac{1}{3} q^a q^b q^c \right). \] (17)
Finally the CS action given by

\[ I_3 = \int_{\mathcal{M}'} \varepsilon_{abc} \left( \hat{R}^{ab} q^c + \frac{1}{3} q^a q^b q^c \right). \] (17)

becomes, upon integration along \( S^1 \),

\[ I_3 = 2 \int_{\mathcal{M}} \Phi R \sqrt{g} d^2x. \]
## AdS tractor connection

### Properties $\rho_{\nu\beta}$

For $d > 3$ tensor $\rho_{\nu\beta}$ satisfies the relation

$$R_{\mu\nu\alpha\beta} = W_{\mu\nu\alpha\beta} + g_{\mu\alpha}\rho_{\nu\beta} - g_{\nu\alpha}\rho_{\mu\beta} - g_{\mu\alpha}\rho_{\nu\alpha} + g_{\nu\beta}\rho_{\mu\alpha},$$  \hspace{1cm} (18)

where $W_{\mu\nu\alpha\beta}$ is the Weyl tensor.
AdS tractor connection

Propeties $\rho_{\nu\beta}$

For $d > 3$ tensor $\rho_{\nu\beta}$ satisfies the relation

$$R_{\mu\nu\alpha\beta} = W_{\mu\nu\alpha\beta} + g_{\mu\alpha} \rho_{\nu\beta} - g_{\nu\alpha} \rho_{\mu\beta} - g_{\mu\alpha} \rho_{\nu\alpha} + g_{\nu\beta} \rho_{\mu\alpha},$$  \hspace{1cm} (18)

where $W_{\mu\nu\alpha\beta}$ is the Weyl tensor.

This can be rewritten equivalently in differential forms formalism as

$$R^{ij} = \frac{1}{2} W^{ij}_{\ kl} e^k e^l - 2(e^i \rho^j - e^j \rho^i).$$  \hspace{1cm} (19)
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2n+1 AdS 2n Conformal

Generically
With the identification

\[ \hat{\omega}^{ij} = \omega^{ij} \]
\[ \hat{\omega}^i_{\ 2n+1} = e^i + \rho^i \]
\[ \hat{\omega}^{2n+1\ 2n+2} = \Phi(x) d\varphi = q^{2n+1} \]
\[ \hat{\omega}^i_{\ 2n+2} = e^i - \rho^i = q^i, \quad (20) \]

with \( i = 1, \ldots, 2n \).
2n+1 AdS 2n Conformal

Chern Simons

The CS action becomes

\[ I_{CS}^{2n+1} = \int \varepsilon_{i_1\ldots i_{2n}} \left( (R^{i_1i_2} + 4\rho^{i_1} e^{i_2}) \ldots (R^{i_{2n-1}i_{2n}} + 4\rho^{i_{2n-1}} e^{i_{2n}}) \right) \Phi d\varphi \]
In terms of Weyl

The previous CS action, upon integration along $S^1$, becomes

$$I_{CS} = \int \Phi \delta_{j_1 \ldots j_{2n}}^{i_1 \ldots i_{2n}} \left( W_{i_1 j_1}^{i_2 j_2} \ldots W_{i_{2n-1} j_{2n-1}}^{i_{2n} j_{2n}} \right) |e| d^{2n}x. \quad (21)$$
2n+1 AdS 2n Conformal

To be noticed

- This is simpler than it seems as $W^i_{jk} = 0$.
- This is very similar to the Euler density but where Riemann tensor has been replaced by Weyl tensor.
5 AdS and 4 Conformal

The usual conformal with a twist

\[ I_{CS}^4 = \int \Phi \left( W^{\mu\nu\alpha\beta} W_{\mu\nu\alpha\beta} \right) \sqrt{g} d^4x \]

which is a generalization of the usual Weyl Gravity mentioned at the beginning.
Chern Simons theories can describe a simple generalization of Weyl Gravities.
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- The Weyl gravities obtained for $d > 4$ have non-arbitrary coefficient. This is due to hidden AdS symmetries.
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- These are mere the zero modes of the compactification. A lot to do.
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- The Weyl gravities obtained for $d > 4$ have non arbitrary coefficient. This is due to hidden AdS symmetries.
- These are mere the zero modes of the compactification. A lot to do.
- A higher spin version of this is calling on.