Coarse graining, diffeomorphism symmetry and perfect actions in quantum gravity ... and much much more

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Canonical and Covariant Dynamics
of Quantum Gravity

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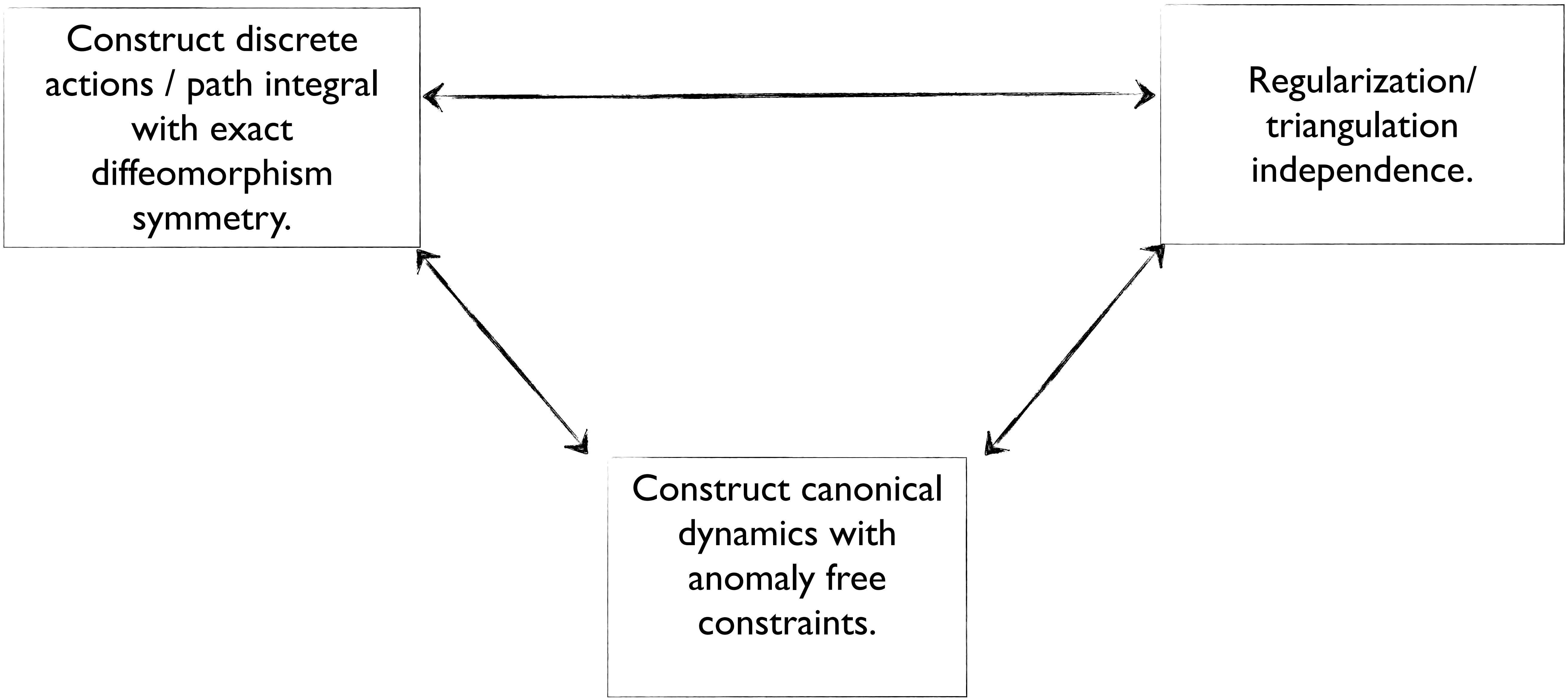
Main Message

Construct discrete actions / path integral with exact diffeomorphism symmetry.

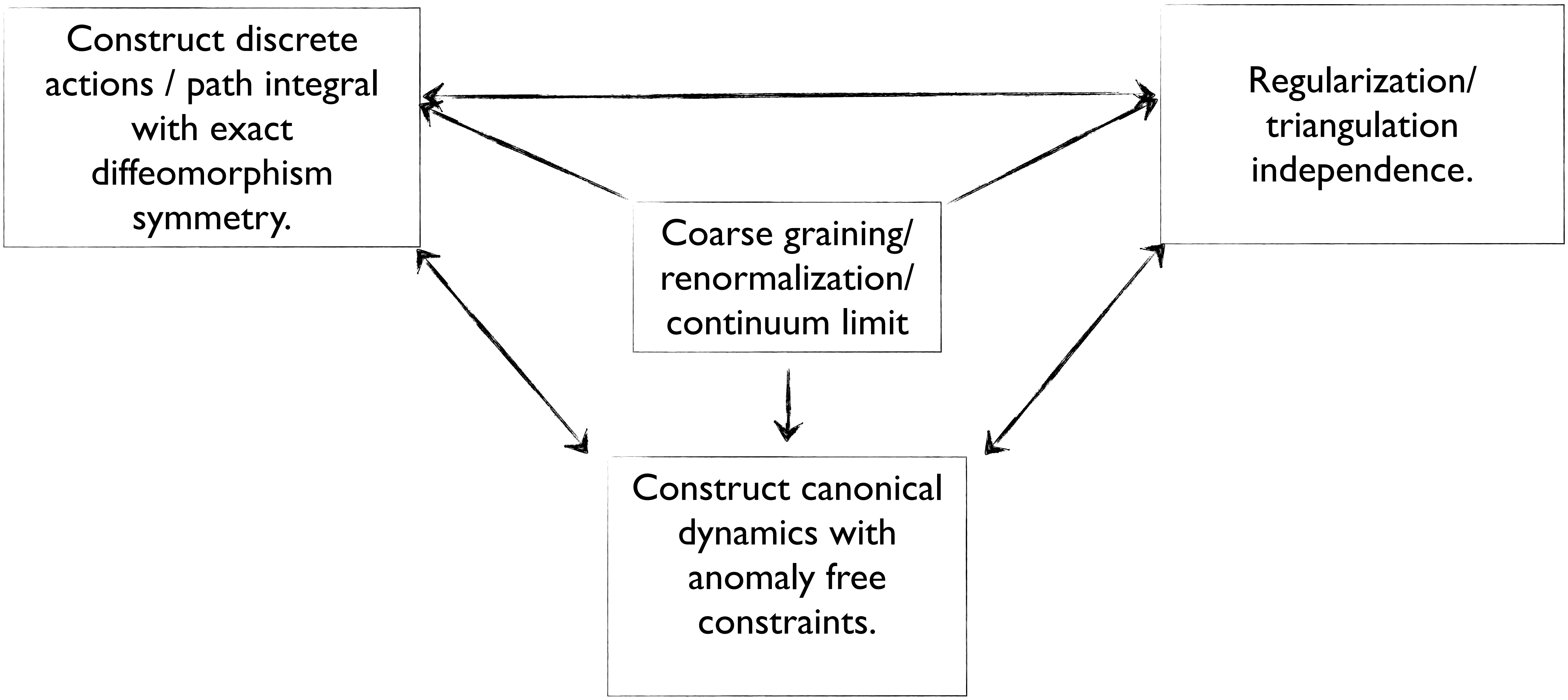
Regularization/ triangulation independence.

Construct canonical dynamics with anomaly free constraints.

Main Message



Main Message



Overview

A. What is diffeomorphism symmetry for discrete gravity?

B. What is a perfect action?

C. Coarse graining 1d models

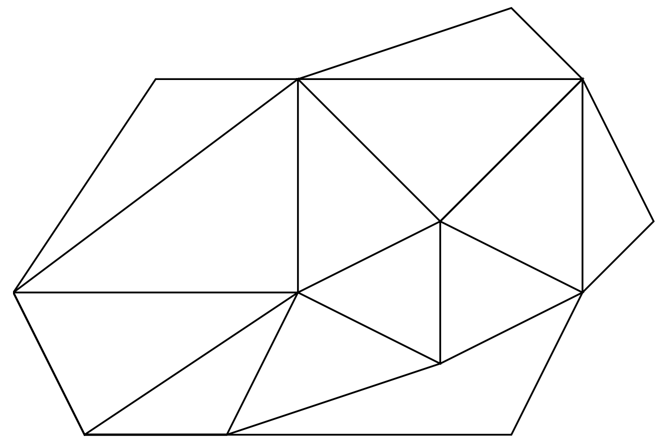
D. Coarse graining higher dimensional models

E. Canonical formalism for discrete theories

F. Conclusions

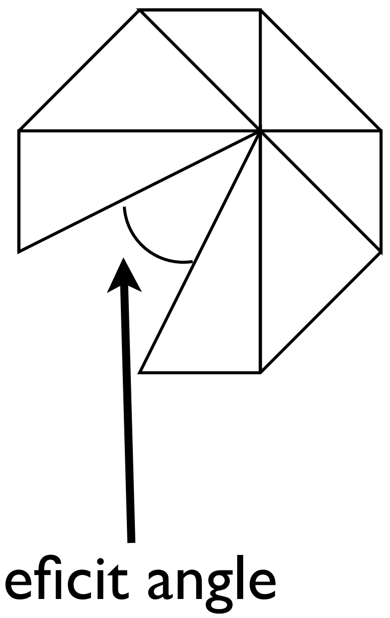
What is diffeomorphism symmetry in the discrete?

Set up



- triangulation
- labels giving geometric data: variables
- prescription how to rebuild geometry

- action as function of labels: encodes dynamics/solutions



Regge calculus

- length variables associated to edges
- deficit angles: curvature
- Regge action

Regge action

- one choice of discretization:

$$S_{cont} = \int d^D x \sqrt{g} \left(\tfrac{1}{2} R - \Lambda \right)$$

$$S_{discr} = \sum_{\text{hinges}\, h} F_h \epsilon_h - \Lambda \sum_{\text{simplices}\, \sigma} V_\sigma$$

4d:triangles
3d: edges

volume of triangle/edge

deficit angle

volume of 4-simplex/ tetrahedron

Gauge symmetries

•**gauge symmetries**: given some fixed boundary conditions solutions (extrema of the actions) are NOT unique

•for boundary conditions describing flat space: solutions are non-unique
•non-uniqueness described by **vertex translations**
⇒gauge symmetries for these configurations

•3d gravity: locally flat solutions (deficit angles vanishing)
•boundary: tetrahedron (surface) with fixed lengths
•variables: four inner edges

•3-parameter set of solutions given by choosing position of vertex in the flat tetrahedron
•⇒ vertex translations

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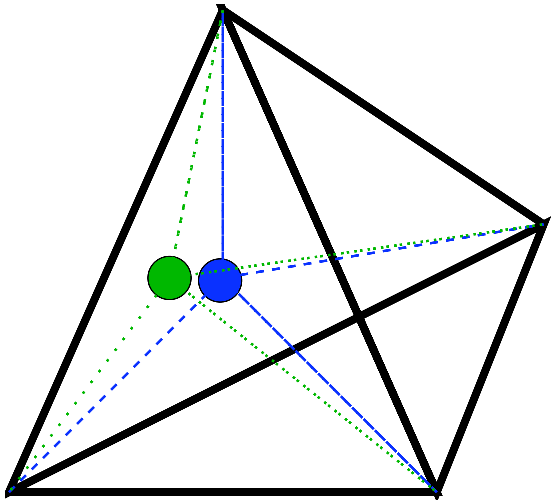

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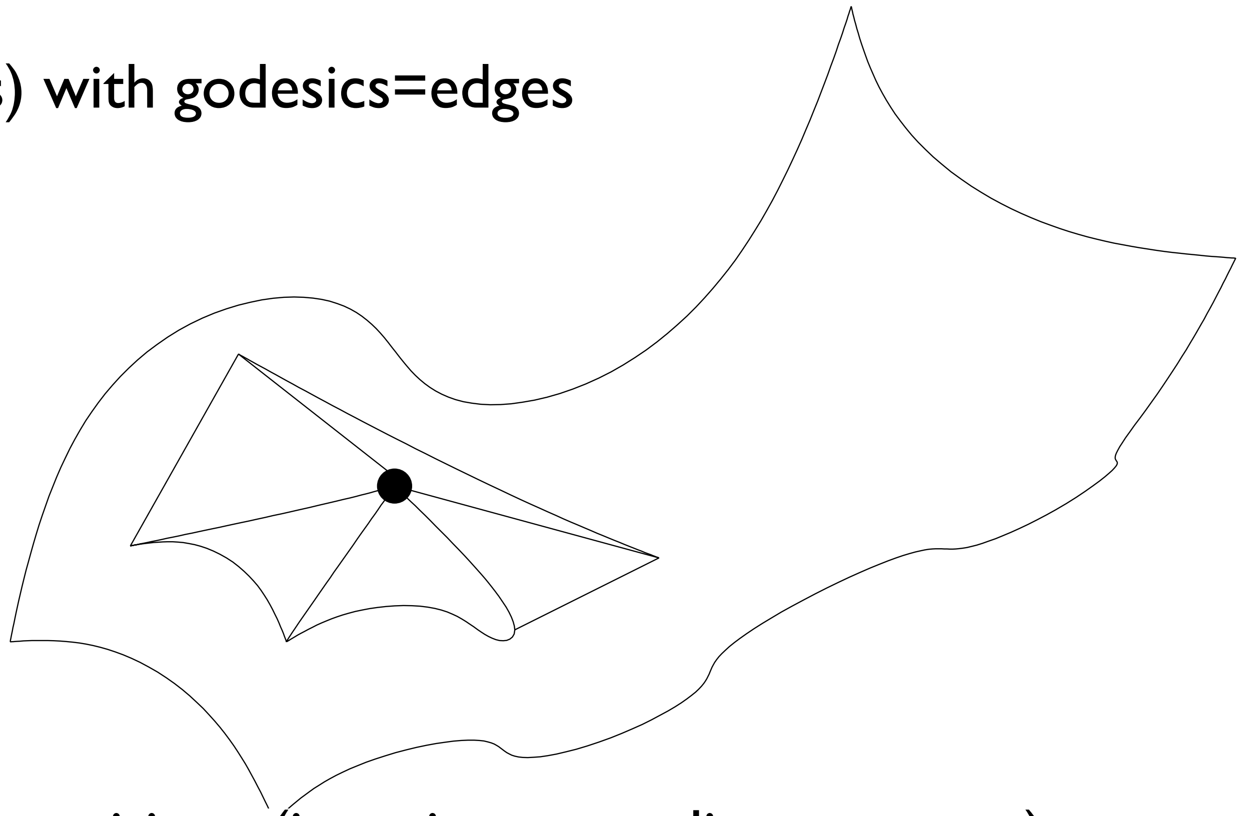
•3-parameter set of solutions given by choosing position of vertex in the flat tetrahedron
•⇒ vertex translations

Gauge symmetries ?

- assume we would have a discretization (discrete action) that would re-produce all the continuum solutions in the following sense:
    - take any continuum solution
    - triangulate (choose positions of vertices) with godesics=edges
    - label edges with geodesic lengths



- expect that solutions just differing by vertex positions (in a given coordinate system) are physically equivalent
- these solutions nevertheless generally differ in their edge lengths (see previous example)
- $\Rightarrow$gauge equivalence of these configurations

We will call such an amazing action a perfect action.

- do we have such a discretization (with such amazing properties)?

⇒unfortunately not in 4d

⇒only for 3d without (Regge ’61) and with (Bahr, BD ‘09) cosmological constant

Later: How could we become perfect?

How do we know?

- criterium: non-uniqueness of solutions for fixed boundary conditions

  - $$\det\left(\frac{\partial^2 S}{\partial x^i \partial x^j}\right)\Big|_{\text{solution}} = 0$$

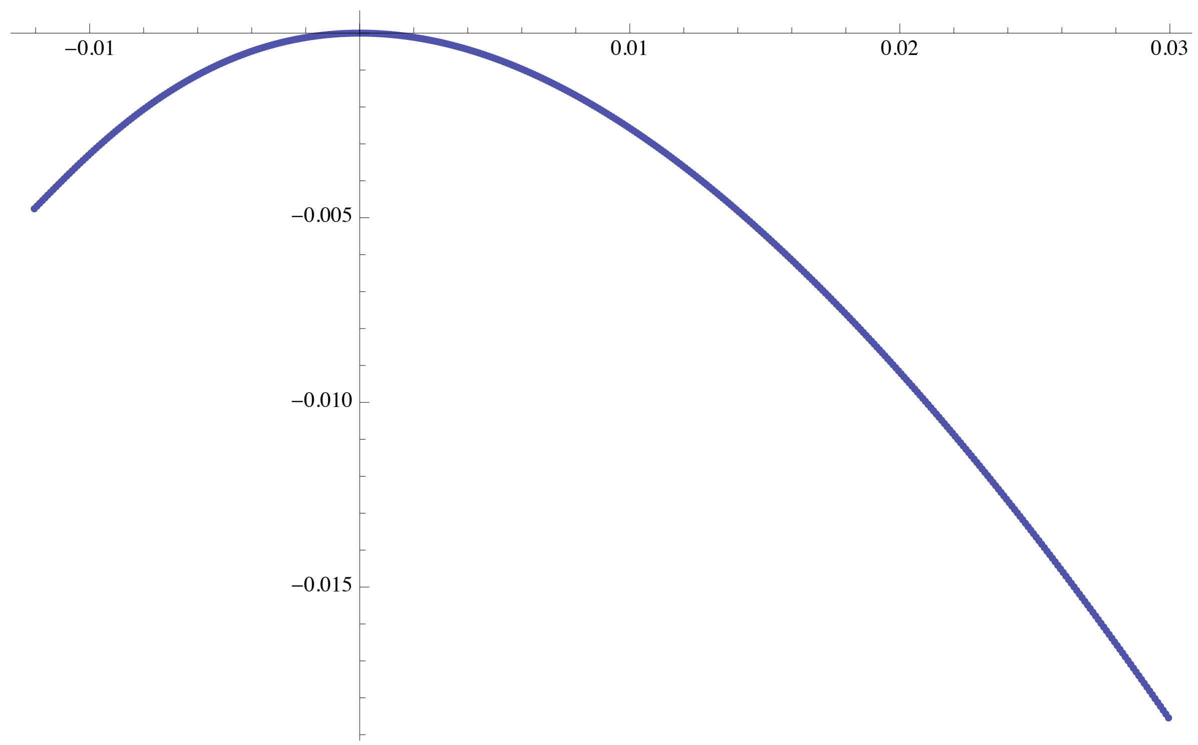
- i.e. the Hessian of the action has zero eigenvalues (null modes=gauge modes)

- existence of symmetries depends on dynamics (that is action)!
- different solutions might have gauge orbits of different size
- invariance of action not sufficient for gauge symmetry

- criterium relevant for
  - canonical analysis (only degenerate Lagrangians lead to constraints!)
  - perturbative expansion
  - counting of physical degrees of freedom

For (a) curved Regge solution: symmetries are broken.

[Bahr, BD 09]



lowest eigenvalues of Hessians as function of deviation parameter from 4d flat solution (curvature)

Symmetry is broken, effect quadratic in curvature.

Why do we care?

•diffeomorphism symmetry very strong requirement: resolve (otherwise overwhelmingly many) ambiguities
⇒we can show that explicitly in 1d models

⇒equivalence to triangulation / discretization independence

•gauge symmetries reduce number of physical degrees of freedom
⇒if diffeomorphism symmetries are broken lattice acts as kind of aether

•important to understand structure of gauge symmetries, as these lead to divergencies in path integral
⇒broken symmetries are complicated to deal with

•canonical quantization: need closed constraint algebra (main problem)
⇒can be obtained with a perfect action

1d models:

reparametrization invariant dynamics

1d reparametrization invariant systems

continuum:

- take q and t as variables
- use auxilary parameter evolution parameter s
- solutions $t(s), q(s)$ invariant under reparametrizations in s

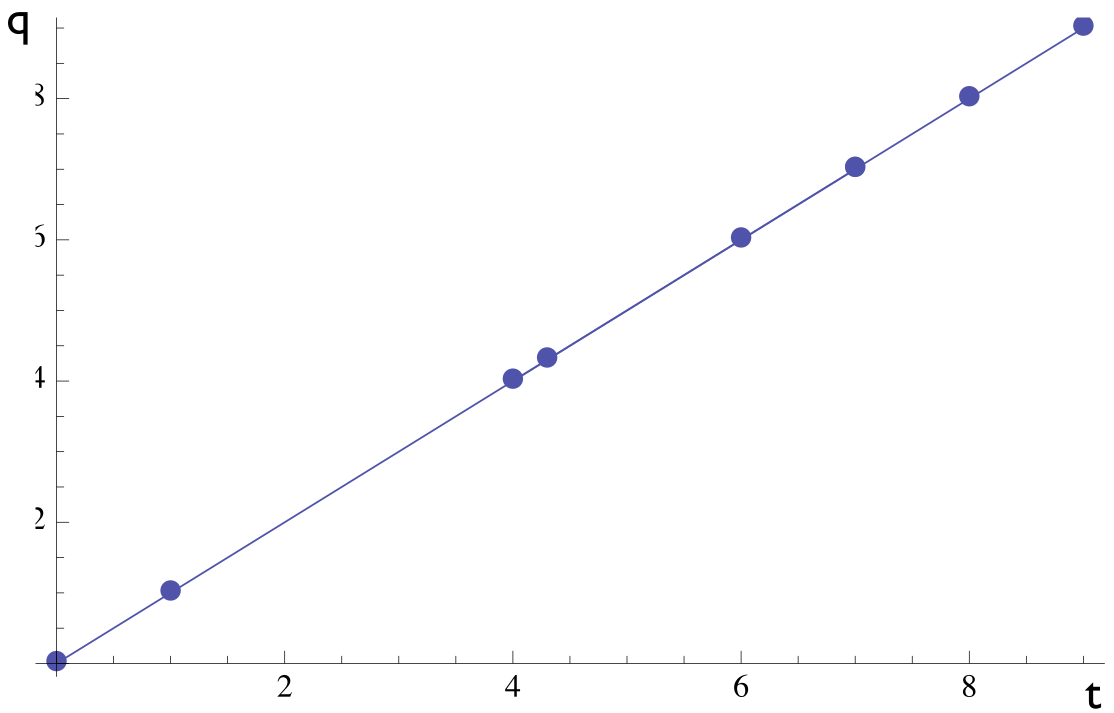
$$L = t' \left(\frac{m}{2} \frac{q'^2}{t'^2} - V(q) \right)$$

discretization $\quad s \longrightarrow n$

$$L(n, n+1) = (t_{n+1} - t_n) \left(\frac{m}{2} \frac{(q_{n+1} - q_n)^2}{(t_{n+1} - t_n)^2} - V\left(\frac{1}{2} q_n + \frac{1}{2} q_{n+1}\right) \right)$$

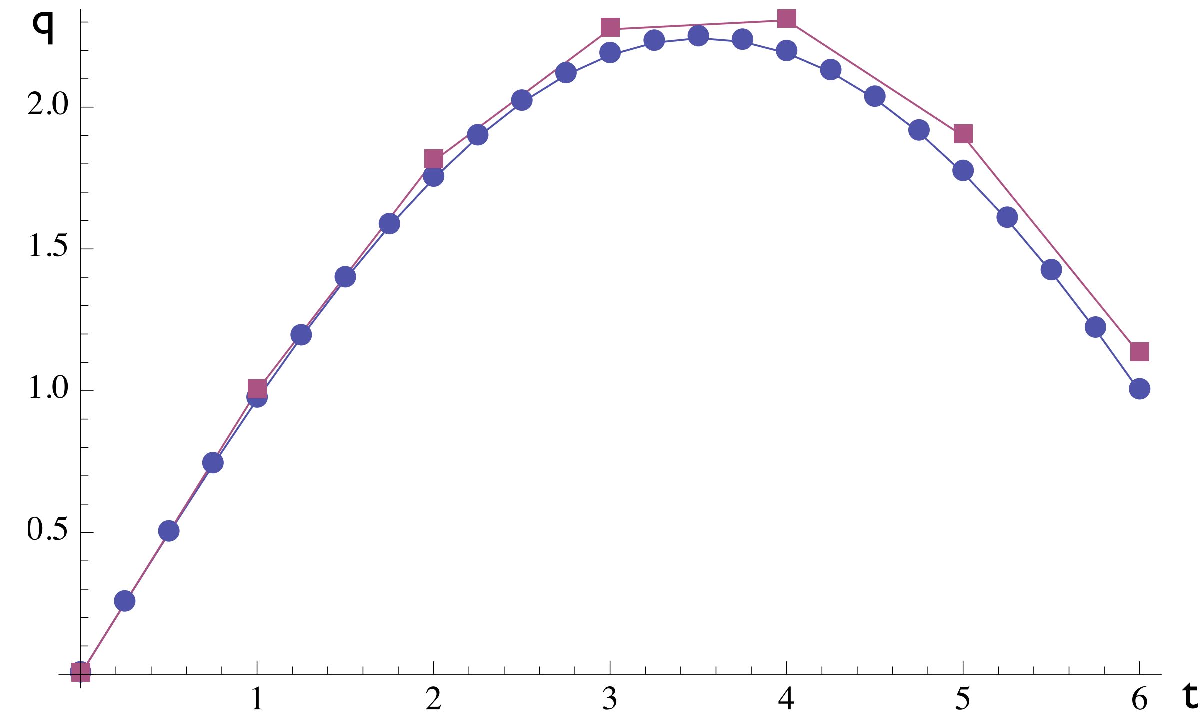
- vertex translations symmetry for $V = 0$
- symmetry broken for $V \neq 0$ [Gamini Pullin 03, Marsden West 01]

Examples



vanishing potential

- position of vertices arbitrary
- one gauge mode
- refinement independent

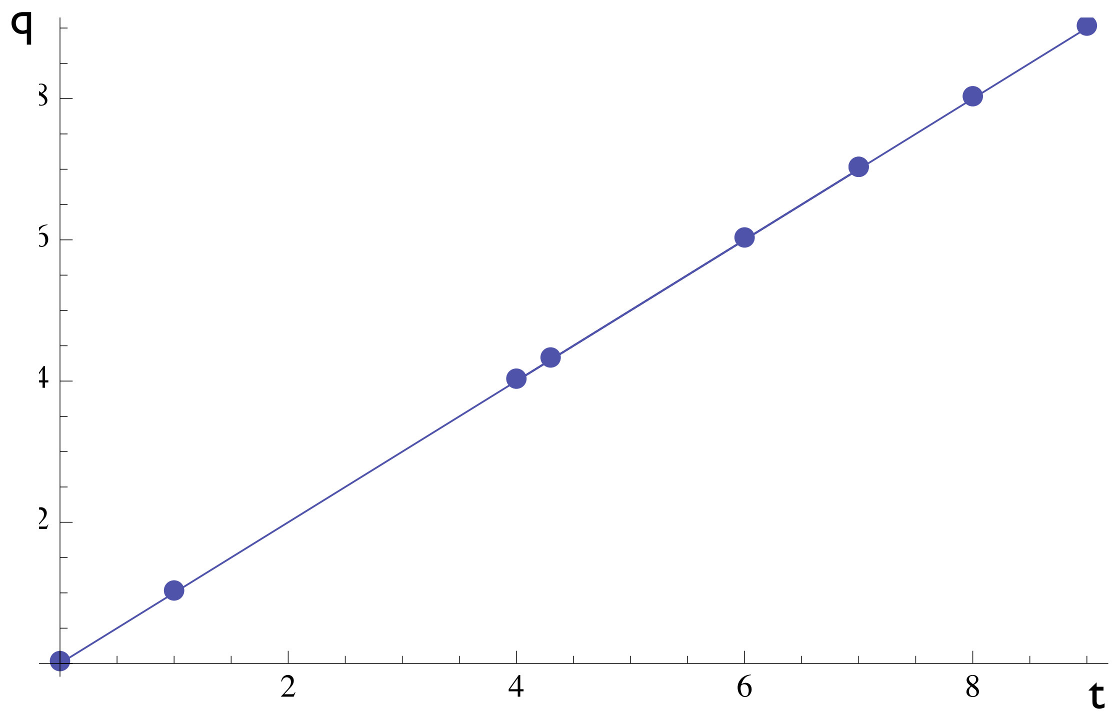


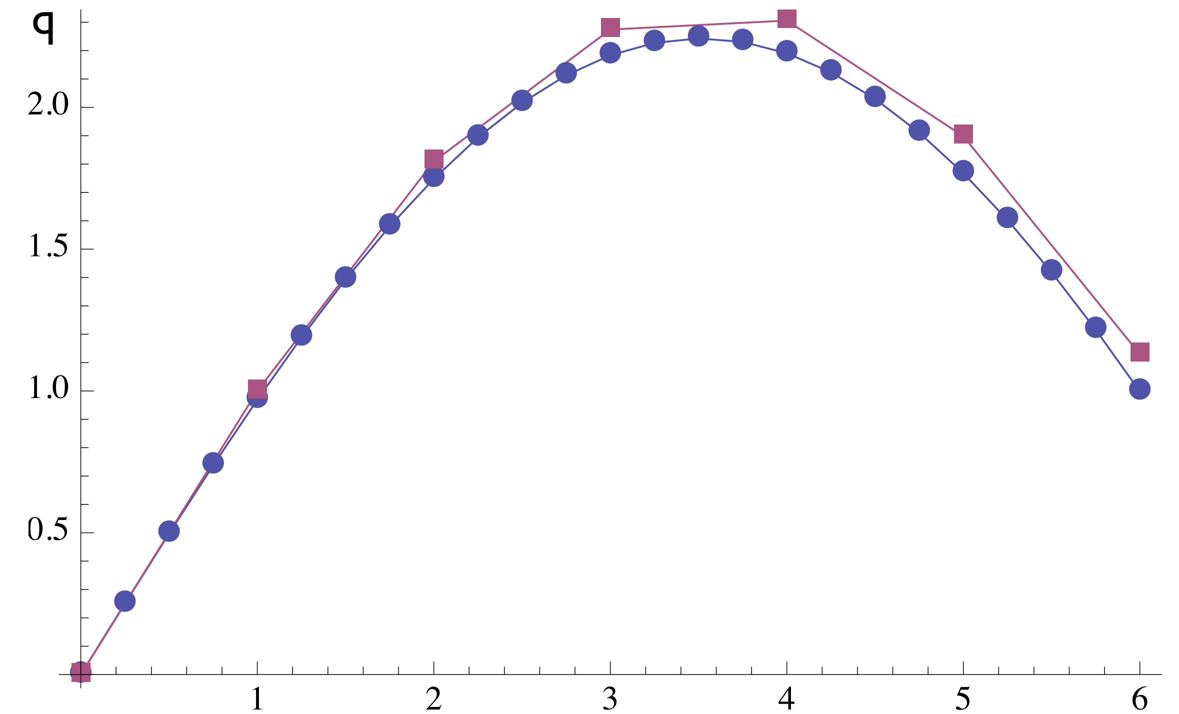
quadratic potential

- position of vertices fixed
- one pseudo gauge mode
- refinement dependent

- Reparametrization symmetry (=vertex translation symmetry) broken!

Examples





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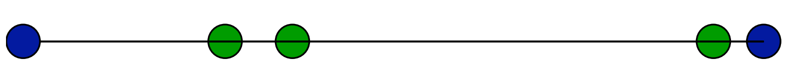

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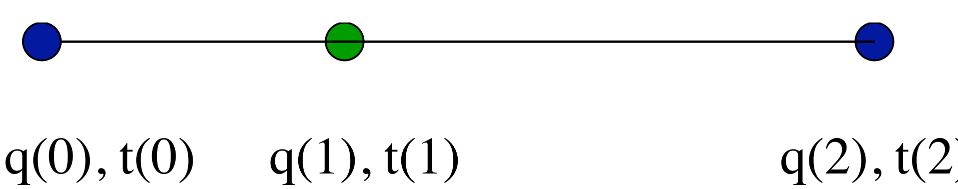
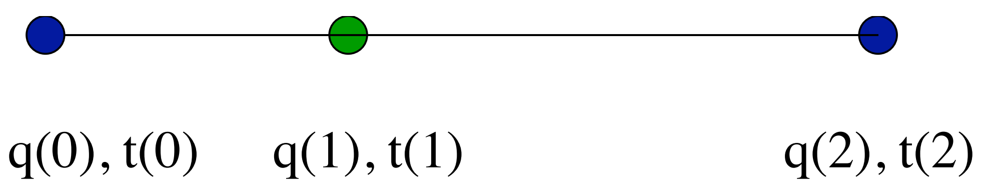


Vertex translation symmetry



- vertex translation symmetry is there, if there is a solution for arbitrary choice of t(1)
- however for non-vanishing potential and generic discretizations: t(1) uniquely fixed

What would happen, if we would have a (quantum) model with vertex translation symmetry?

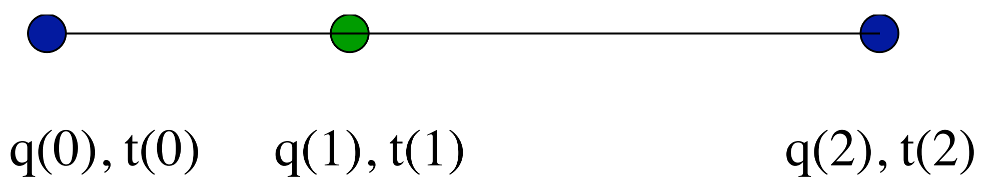
$$K(q_0, t_0, q_1, t_1) \; K(q_1, t_1, q_2, t_2)$$

discrete path integral:

- associate amplitude (propagator) to edges
- integrate over (bulk) variables

1d quantum model

$$K(q_0, t_0, q_1, t_1) \quad K(q_1, t_1, q_2, t_2)$$



discrete path integral:

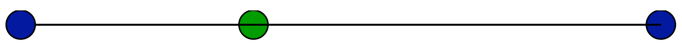
•associate amplitude (propagator) to edges

•integrate over (bulk) variables

$$\langle q_0, t_0 | q_2, t_2 \rangle := Z(q_0, t_0, q_2, t_2) \; := \; \int dq_1 dt_1 \; K(q_0, t_0, q_1, t_1) K(q_1, t_1, q_2, t_2)$$

Vertex translation symmetry ⇒discretization independence

[Bahr, BD, Steinhaus 2011]



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- assume amplitude is invariant under vertex translations
- gauge fix the t variable:

$$Z(q_0, t_0, q_2, t_2) \; := \int dq_1 \; K(q_0, t_0, q_1, t_1^f) K(q_1, t_1^f, q_2, t_2)$$

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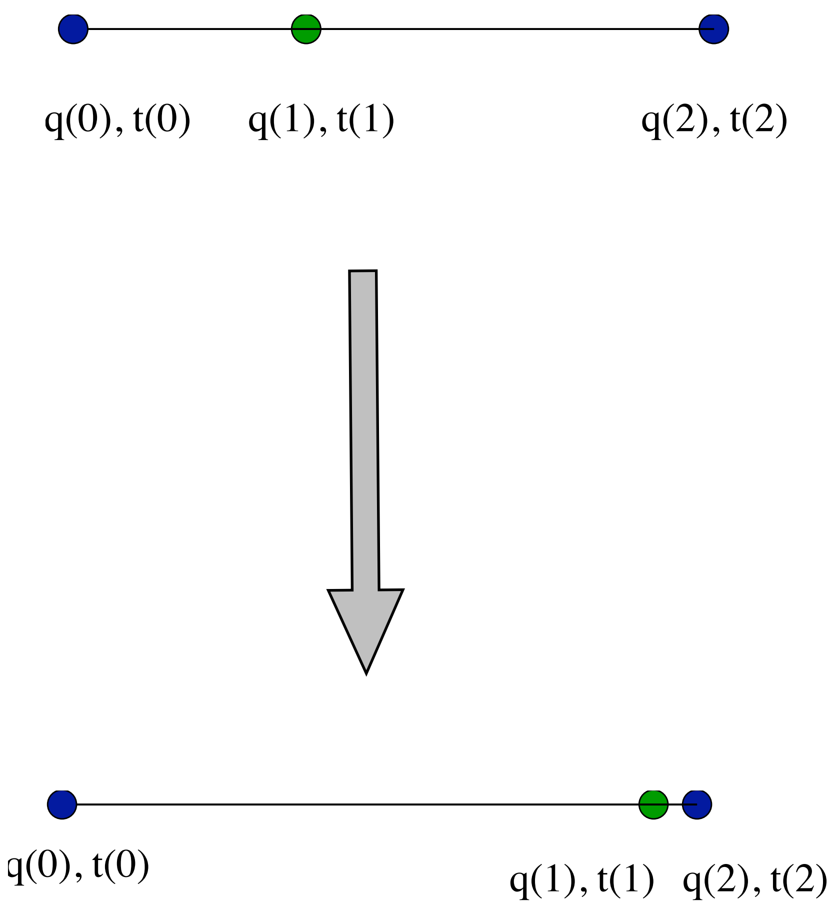

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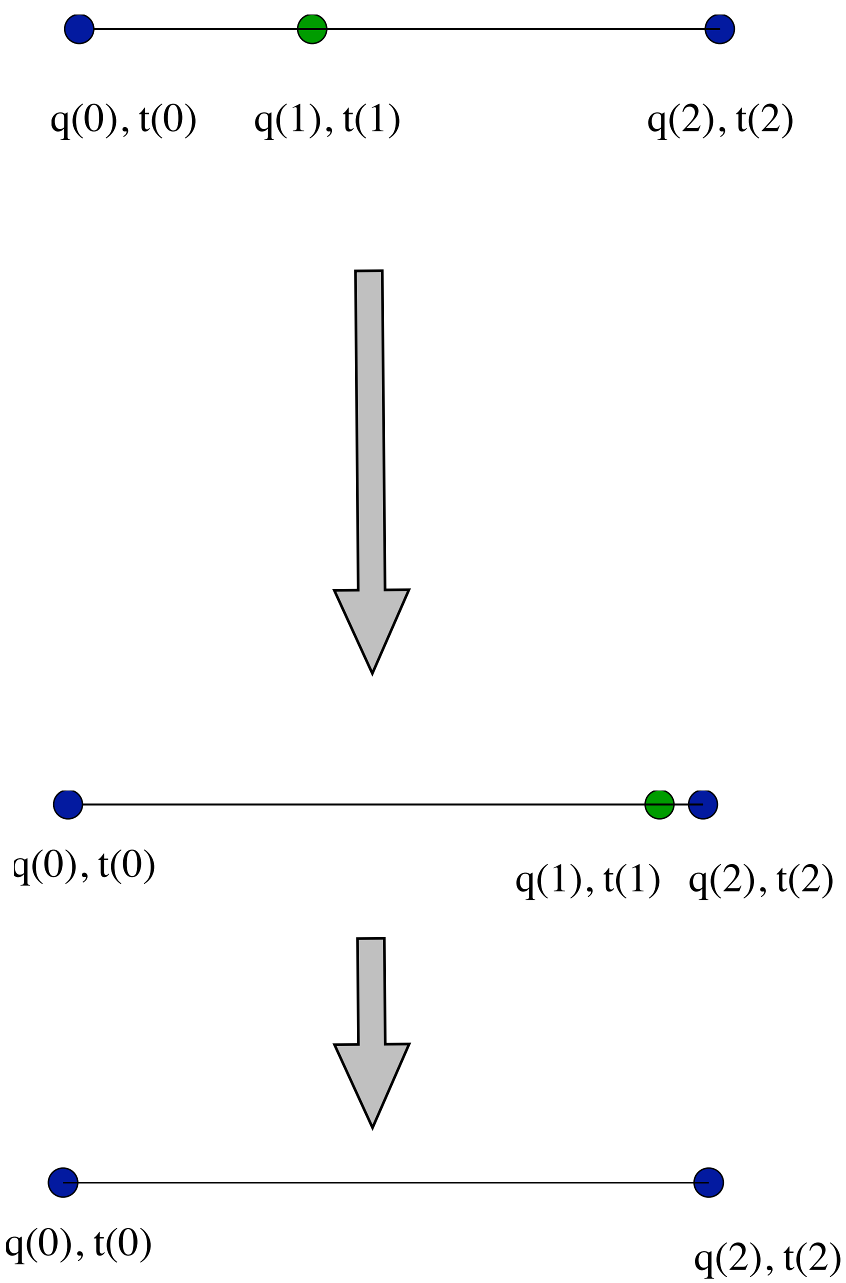
$$t_1^f \longrightarrow t_2 : \qquad K(q_1, t_1^f, q_2, t_2) \rightarrow \delta(q_1 - q_2)$$

Vertex translation symmetry ⇒discretization independence

[Bahr, BD, Steinhaus 2011]



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$$t_1^f \to t_2 : \qquad K(q_1, t_1^f, q_2, t_2) \to \delta(q_1 - q_2)$$

$$K(q_0, t_0, q_2, t_2) \ = \int dq_1 \ K(q_0, t_0, q_1, t_1) K(q_1, t_1, q_2, t_2)$$

discretization independence!

Uniqueness: no discretization ambiguities

$$K(q_0, t_0, q_2, t_2) = \int dq_1 \; K(q_0, t_0, q_1, t_1) K(q_1, t_1, q_2, t_2)$$

Assuming vertex translation symmetry (and local amplitude) we derived discretization independence.

Transition amplitude can be computed with no subdivisions at all:

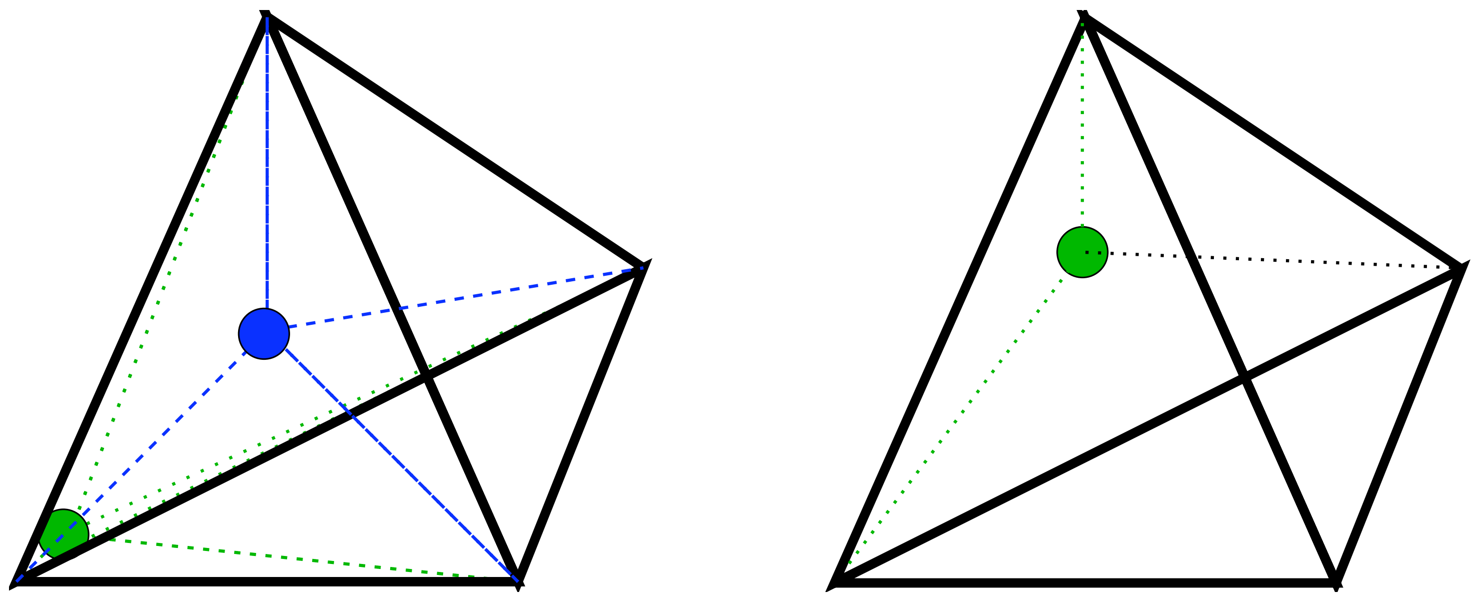
$$\langle q_0, t_0 | q_2, t_2 \rangle = K(q_0, t_0, q_2, t_2)$$

Discrete amplitude given by (continuum) transition amplitude.

Therefore the amplitude is **unique** (if you want to reproduce continuum physics in the continuum limit).

To obtain this amplitude requires to solve the dynamics.

Higher dimensions?



Similar argument as in 1d possible?

What are the conditions for these limits?
Non-local amplitudes (in 4d, 3d with matter)?

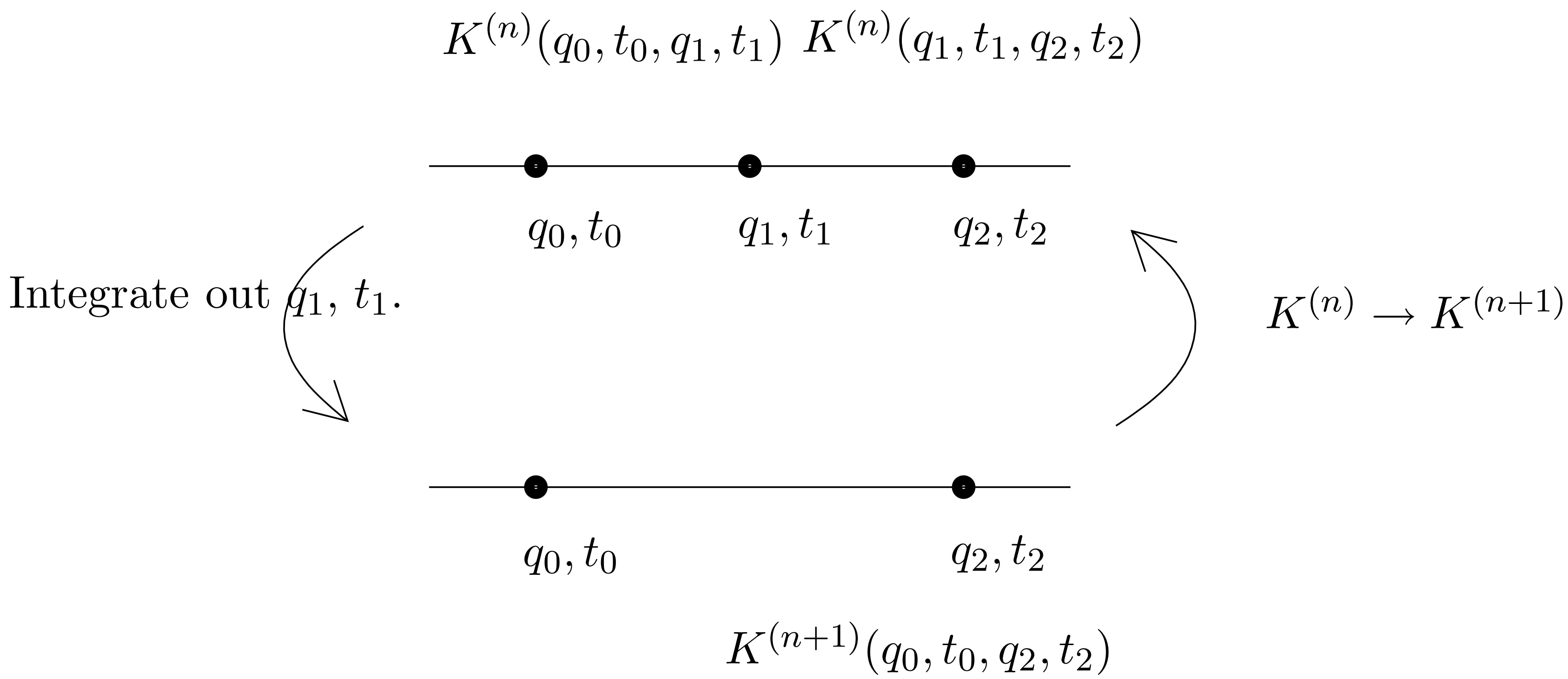
How to obtain perfect discretizations?

- we have seen that perfect discretization coincides with the continuum propagator
- this can be obtained by solving the path integral, which usually involves discretization and taking the continuum limit

- alternatively: consider iterative method
  - integrate out every second vertex: obtain new `effective’ amplitude
  - iterate, obtain lots of effective amplitudes
  - look for fixed points: continuum limit
  - this is a version of Wilsonian Renormalization group method

- method allows to classify discretization choices (couplings) into relevant and irrelevant ones

Iteration procedure



- converges to continuum propagator (as we just re-sorted integrations in the path integral)
- more convenient: do not start with specific discrete propagator but consider a family of propagators, which closes under the iteration procedure
- consider fixed point equations for this family

Example: harmonic oscillator

$$K(x_0, x_1, T) \;=\; \eta(T)\ \exp\left[-\frac{1}{\hbar}\left(\alpha_1(T)(x_0^2 + x_1^2) + \alpha_2(T)x_0x_1\right)\right]$$

- defines a family of propagators, that closes under iteration procedure

  ⇒can obtain recursion relations for and eta, alpha coefficients:

$$K^{(n+1)}(x_0, x_2, 2T) = \int dx_1\ K^{(n)}(x_0, x_1, T)K^{(n)}(x_1, x_2, T)$$

$$\alpha_1^{(n+1)}(2T) \;=\; \alpha_1^{(n)}(T) - \frac{\alpha_2^{(n)}(T)^2}{8\alpha_1^{(n)}(T)}$$

$$\alpha_2^{(n+1)}(2T) \;=\; -\frac{\alpha_2^{(n)}(T)^2}{4\alpha_1^{(n)}(T)}$$

$$\eta^{(n+1)}(2T) \;=\; \sqrt{\frac{\pi\hbar}{2\alpha_1^{(n)}(T)}}\ \eta^{(n)}(T)^2$$

Example: harmonic oscillator

$$K^{(0)} = \left(\sqrt{\frac{1}{2\pi\hbar}}T^{-1/2} + \ldots\right)\exp\left[-\frac{1}{\hbar}\left(\frac{1}{2}T^{-1}(q_1-q_0)^2 + ET^0 + \frac{\omega^2}{4}T^1(q_0+q_1)^2 + \ldots\right)\right]$$

$$K^{(\infty)} = \left(\sqrt{\frac{\omega}{2\pi\hbar\sinh(\omega T)}}\right)\exp\left[-\frac{1}{\hbar}\left(\frac{\cosh(\omega T)(x_0^2+x_1^2) - 2x_0x_1}{2\omega^{-1}\sinh(\omega T)} + E\right)\right]$$

unique propagator with reparametrization invariance = continuum propagator

- initial discretization not unique, but only lowest order terms in T are relevant
- behaviour of amplitude for large T is irrelevant
- can show uniqueness of fixed point solutions
- only fixed point propagator satisfies (quantum) constraints (Schroedinger equation)

Can we guess perfect discretizations?

Can we guess: anharmonic oscillator?

[Bahr, BD, Steinhaus 2011]

Naive discretization

$$S_{naiv}(q_0,t_0,q_1,t_1) = \frac{1}{2}\frac{(q_1-q_0)^2}{T} + \frac{\omega^2}{4}(q_0^2+q_1^2)T + \frac{\lambda}{2\cdot 4!}(q_0^4+q_1^4)T$$

$$\mu = \sqrt{\frac{1}{2\pi\hbar T}}$$

Can we guess: anharmonic oscillator?

[Bahr, BD, Steinhaus 2011]

Naive discretization → (coarse graining procedure) → Discretization with vertex translation symmetry

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$$S_{perf}(q_0,t_0,q_1,t_1) = \frac{\omega}{2}\frac{\cosh(T\omega)(q_0^2+q_1^2)-2q_0q_1}{\sinh(T\omega)} + \frac{\lambda}{768\omega\sinh^4(T\omega)}\Big[\Big(12T\omega-8\sinh(2T\omega)+\sinh(4T\omega)\Big)(q_0^4+q_1^4) + \Big(-48T\omega\cosh(T\omega)+36\sinh(T\omega)+4\sinh(3T\omega)\Big)(q_0q_1^3+q_0^3q_1) + \Big(24T\omega(2+\cosh(2T\omega))-36\sinh(2T\omega)\Big)q_0^2q_1^2\Big] + O(\lambda^2)$$

$$\mu = \sqrt{\frac{1}{2\pi\hbar T}}$$

$$\mu_{perf} = \sqrt{\frac{\omega}{2\pi\hbar\sinh(T\omega)}}\times \left(1+\lambda\frac{\Big(2+\cosh^2(T\omega)-3T\omega\coth(T\omega)\Big)}{32\omega^2\sinh^2(T\omega)}(q_0^2+q_1^2) + \lambda\frac{\Big(4T\omega+2T\omega\cosh(2T\omega)-3\sinh(2T\omega)\Big)}{32\omega^2\sinh^3(T\omega)}q_0q_1 + -\frac{\lambda\hbar}{64\omega^3}\Big(3\coth(T\omega)-T\omega(2+\frac{3}{\sinh^2(T\omega)})\Big)\right) + O(\lambda^2)$$

anomaly free path integral measure factor
[spin foams: Bojowald, Perez 04]

Example: anharmonic oscillator

- initial discretization not unique, but only lowest order terms in T are relevant
- behaviour of amplitude for large T is irrelevant (universality)
- get also fixed points describing $\dot{x}^2 x^2$ and $\dot{x}^4$ terms in continuum Lagrangian
- only fixed point propagator satisfies (quantum) constraints (Schroedinger equation)

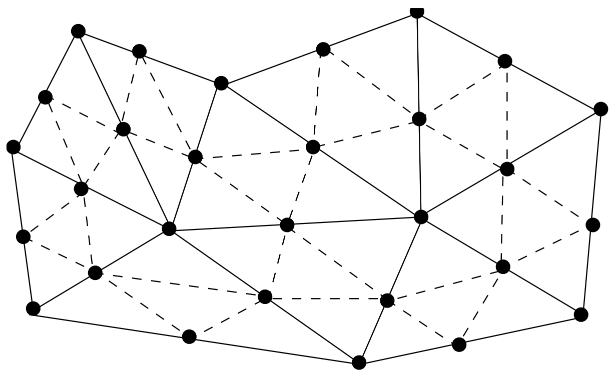
- iterative method / coare graining might be better suited for solving path integrals (for instance in quantum cosmology)

Constructing perfect discretizations for interacting theories is non-trivial.

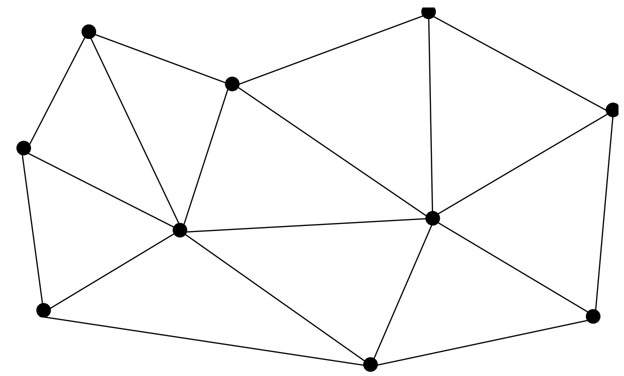
But can be obtained perturbatively.

Method allows to classify the relevance of discretization choices: is gravity renormalizable?

Higher dimensions: 3d gravity with cosmological constant



integrate out small edge lengths



3d Regge with cosmological constant

$$S_{\mathcal{T}} = \sum_e l_e \epsilon_e - \Lambda \sum_\sigma V_\sigma$$

action for flat simplices

broken symmetries,
triangulation dependent

3d Regge with curved simplices
[Bahr, BD 09]

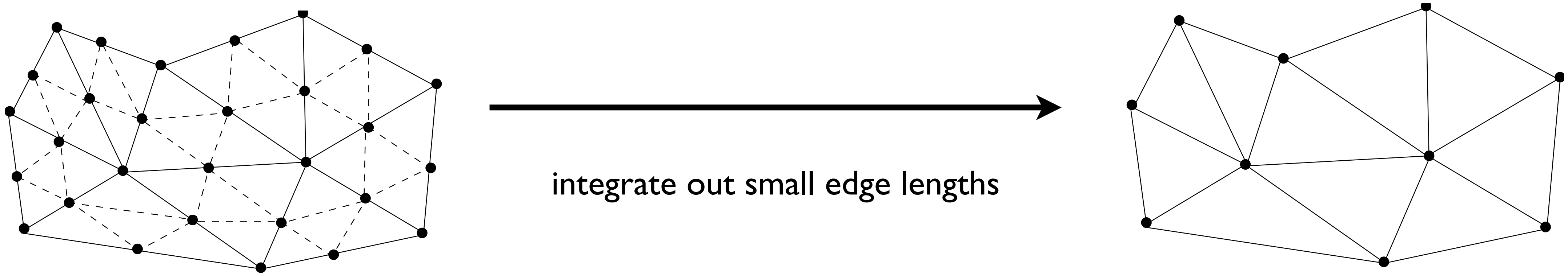
$$S^\kappa_{\mathcal{T}} = \sum_E L_E \epsilon^\kappa_E + 2\kappa \sum_\sigma V^\kappa_\Sigma$$

action for simplices with curvature

$$\kappa = \Lambda$$

exact symmetries,
triangulation independent

Higher dimensions: 3d gravity with cosmological constant



3d Regge with cosmological constant

$$S_{\mathcal{T}} = \sum_e l_e \epsilon_e - \Lambda \sum_\sigma V_\sigma$$

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3d Regge with curved simplices

[Bahr, BD 09]

$$S^\kappa_{\mathcal{T}} = \sum_E L_E \epsilon^\kappa_E + 2\kappa \sum_\sigma V^\kappa_\Sigma$$

action for simplices with curvature

$$\kappa = \Lambda$$

not known explicitly

exact symmetries,
triangulation independent

Higher dimensions: 3d gravity with cosmological constant

3d quantum gravity with cosmological constant and flat simplices
??

→ ??? — integrate out small edge lengths →

Tuarev-Viro model

Here it is ‘easier’ to guess the correct model (from invariance property).

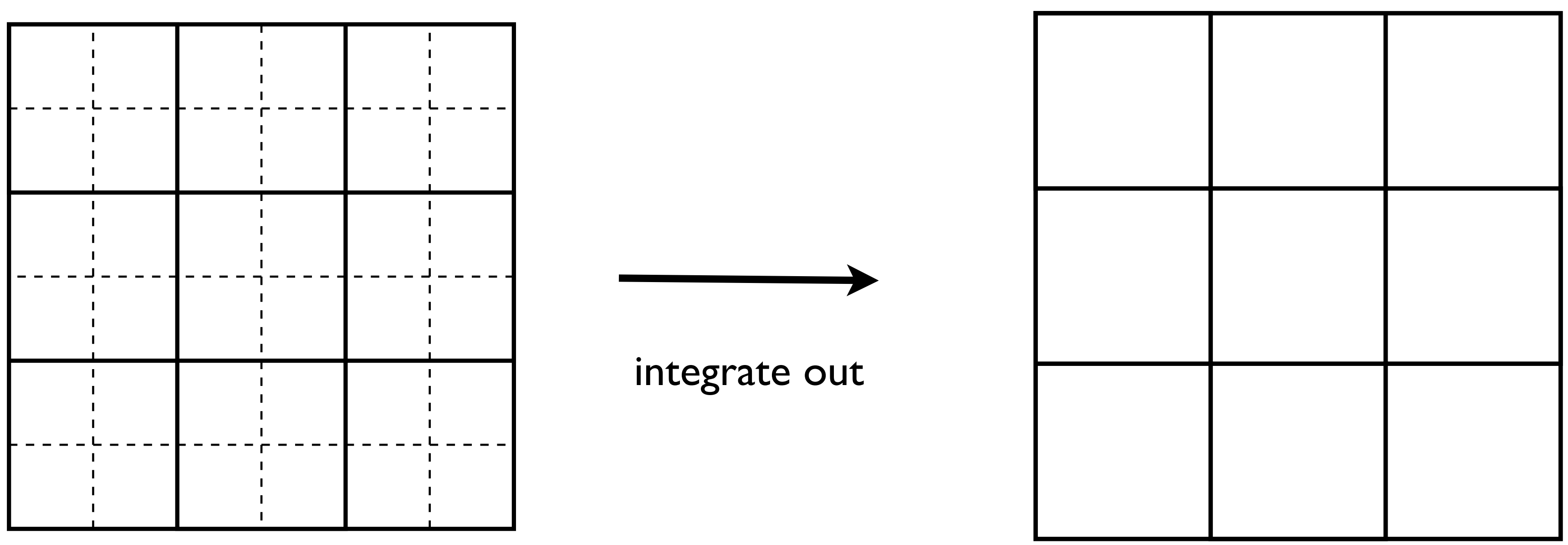
Higher dimensions: free theories [Bietenholz 2000, Bahr, BD, He 2010]

$$S = \frac{a^d}{2} \sum_{x,y} \phi(x) \left(\Delta(x,y) + \mu^2 \delta^{(N)}(x,y) \right) \phi(y)$$

free scalar field
on regular lattice

free electromagnetic field
on regular lattice

free gravitons
on regular lattice



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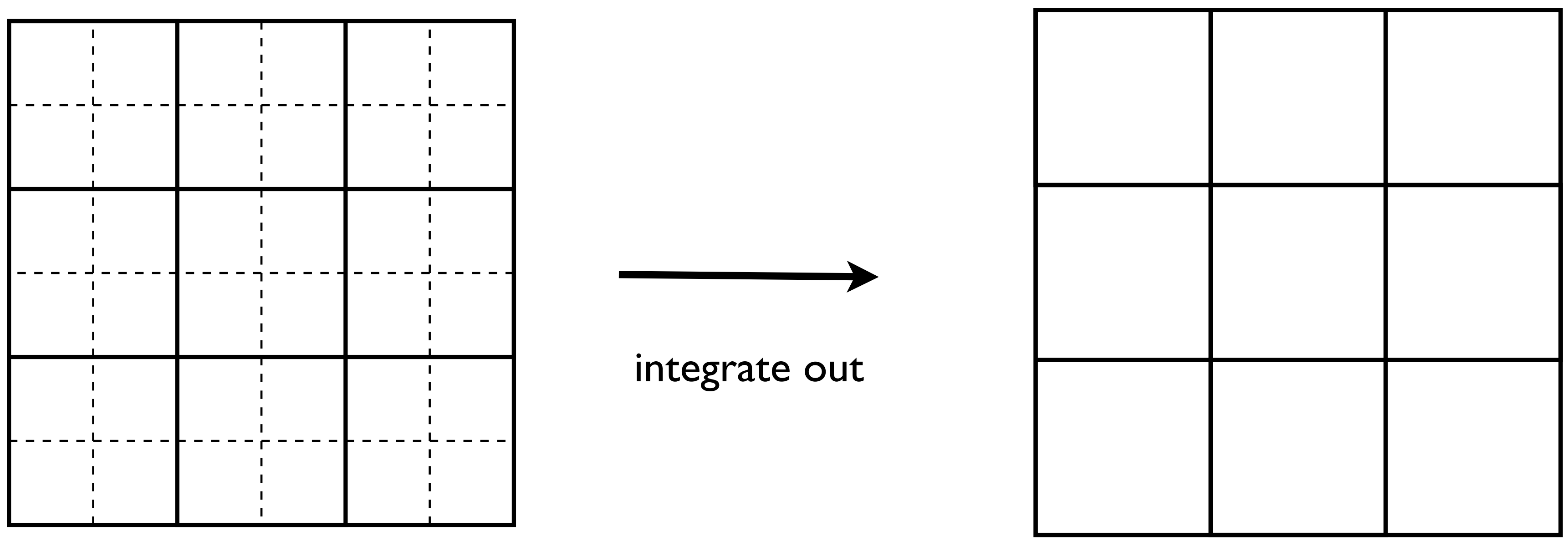
free scalar field
on regular lattice

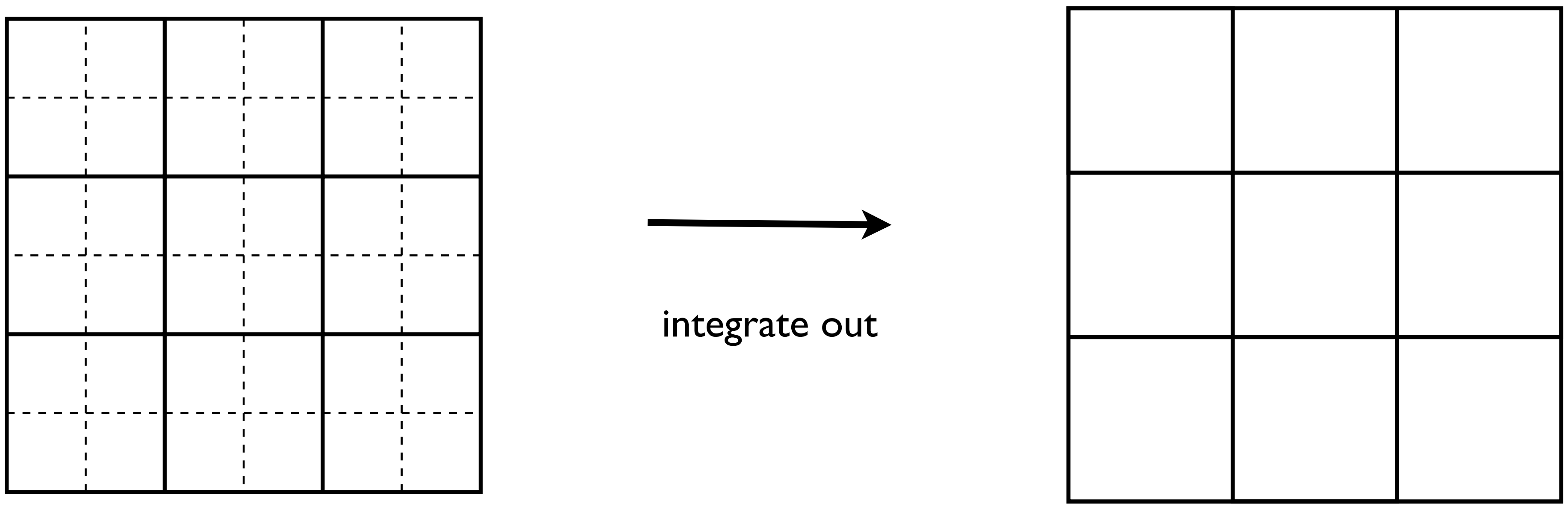
free electromagnetic field
on regular lattice

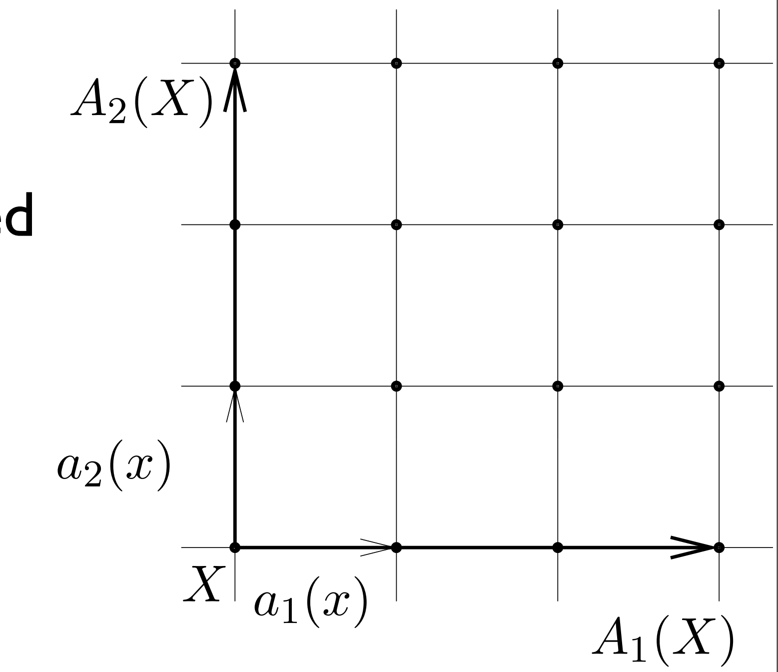
gauge symmetries for
linearized theory

free gravitons
on regular lattice



Coarse graining





- have to choose a coarse graining map
- this is an art (there are many choices which do not work)!
- but in order to regain diffeomorphism symmetry: might be very restricted
- determined by geometric nature of field (scalar field, connection, ...)
- should respect gauge symmetries
- more details in [Bahr, BD, He 2010]
- obtained coarse graining description for metric (averaging problem)

Coarse graining

$$S'\left[\Phi(X)\right] = \operatorname*{extr}_{\phi,\,B\phi=\Phi} S\left[\phi(x)\right]$$

$$\operatorname*{extr}_{\Phi} \operatorname*{extr}_{\phi,\,B\phi=\Phi} S = \operatorname*{extr}_{\phi} S$$

Coarse graining

classically

$$S'\,[\Phi(X)] \;=\; \underset{\phi,\, B\phi=\Phi}{\mathrm{extr}}\; S\,[\phi(x)]$$

coarse grained fields

coarse graining map

microscopic variables

-coarse graining conditions can be implemented via Lagrange multipliers
-solve action with added Lagrange multiplier terms

$$\underset{\Phi}{\mathrm{extr}}\;\underset{\phi,\, B\phi=\Phi}{\mathrm{extr}}\; S \;=\; \underset{\phi}{\mathrm{extr}}\, S$$

-solving in stages (allows for approximations at every stage)
-coarse grained solutions are solutions of coarse grained action

Coarse graining

$$Z = \sum_{\phi} A[\phi] = \sum_{\Phi} \sum_{\phi,\, B\phi = \Phi} A[\phi] = \sum_{\Phi} A'[\Phi]$$

Coarse graining

quantum mechanically

$$Z = \sum_{\phi} A[\phi] = \sum_{\Phi} \sum_{\phi,\, B\phi=\Phi} A[\phi] = \sum_{\Phi} A'[\Phi]$$

- summing in stages
- but not only re-organization of summation:
- allows for approximations
- discussion of relevant and irrelevant couplings (without necessarily having to solve the theory)
- consider space of theories (space of effective actions) and flow in this space instead of one specific model

Higher dimensions: free theories [Bietenholz 2000, Bahr, BD, He 2010]

$$S \;=\; \frac{a^d}{2}\sum_{x,y}\phi(x)\left(\Delta(x,y)+\mu^2\delta^{(N)}(x,y)\right)\phi(y)$$

free scalar field
on regular lattice

$$S' \;\sim\; \frac{1}{2}\sum_{P}\Phi(P)\,M(P)\,\Phi(-P)$$

coarse grained action
(Fourier space)

$$M(P)=\left(\sum_r\left(\frac{1}{\sum_b k_b\bar{k}_b+a^2\mu^2}\right)_{|p=P+N'r}\right)^{-1}$$

$$k_b=1-\exp(2\pi i p_b/N)$$

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- coarse grained action can be explicitly obtained in the `topological cases': 2d EM, 3d gravity (non-trivial calculation: action is invariant)
- and in 2d
- 2d without mass: action is invariant (on regular square lattice)
- with mass: results in non-local effective action
- also in all other non-topological cases

Coarse graining field theories

Coarse graining field theories

- classify coarse graining maps
- even for free theories: diffeomorphism symmetry related to energy-momentum conservation
- numerically: (energy preserving) integration methods
- physically: is there microscopic energy-momentum conservation (Lorentz symmetry)?
- have to consider non-local actions: enlarged phase space?

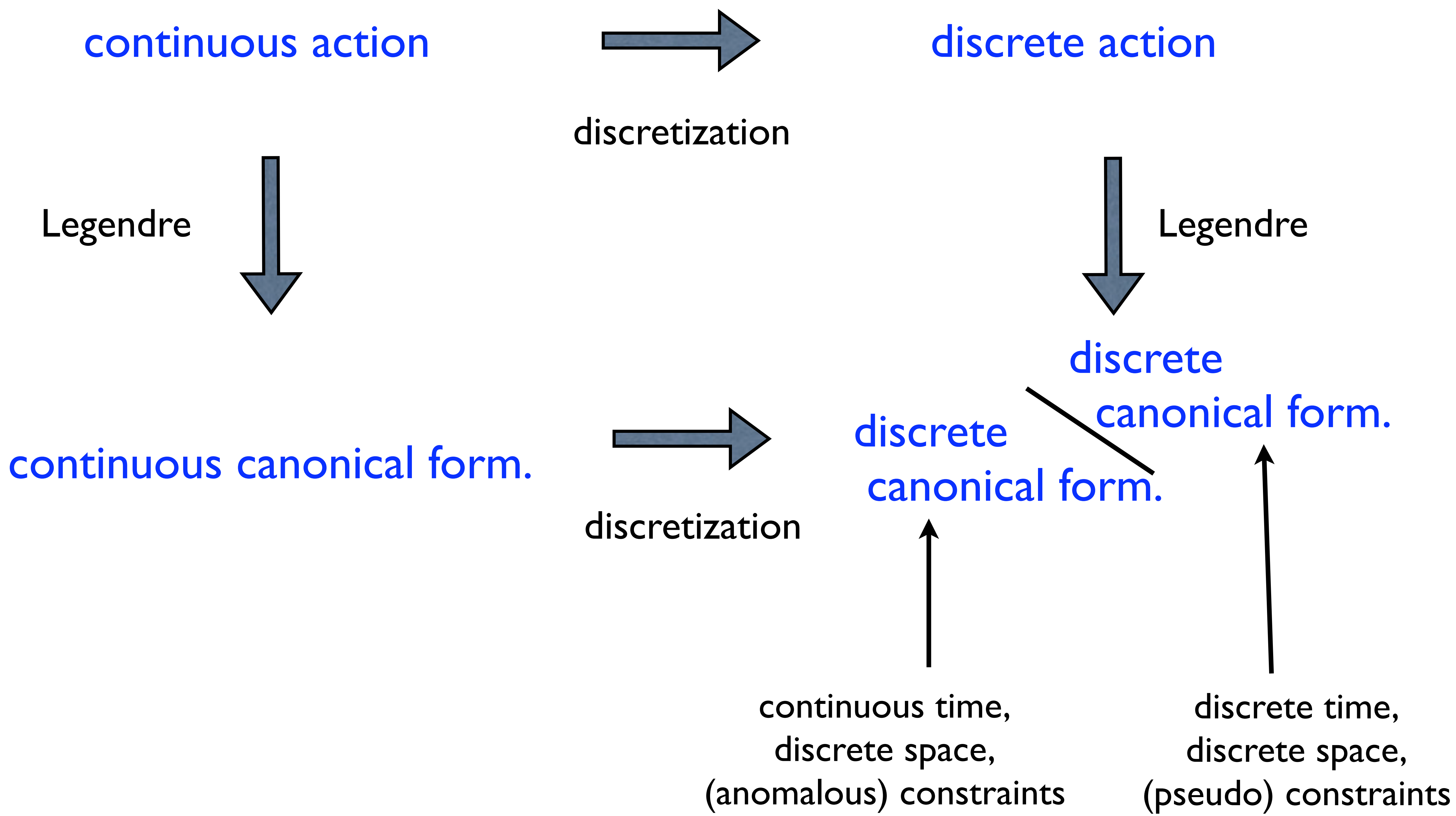
Construct discrete actions / path integral with exact diffeomorphism symmetry.

↔

Construct canonical dynamics with anomaly free constraints.

[Gambini-Pullin 00s, Bahr, BD 09; BD, Hoehn 09, (classical)
Barrett, Crane 97, Bonzom, Freidel 11 (3d quantum);
Bonzom 11 (4d topological, quantum)]

Canonical Frameworks



Canonical Framework

[Bahr, BD '09; BD, Höhn 09]

- evolve spatial hypersurfaces in discrete time steps
- use action as generating function for time evolution map

[consistent discretizations, Gambini & Pullin et al 03-05]

- reproduces (broken) symmetries exactly [Bahr, BD 09] :

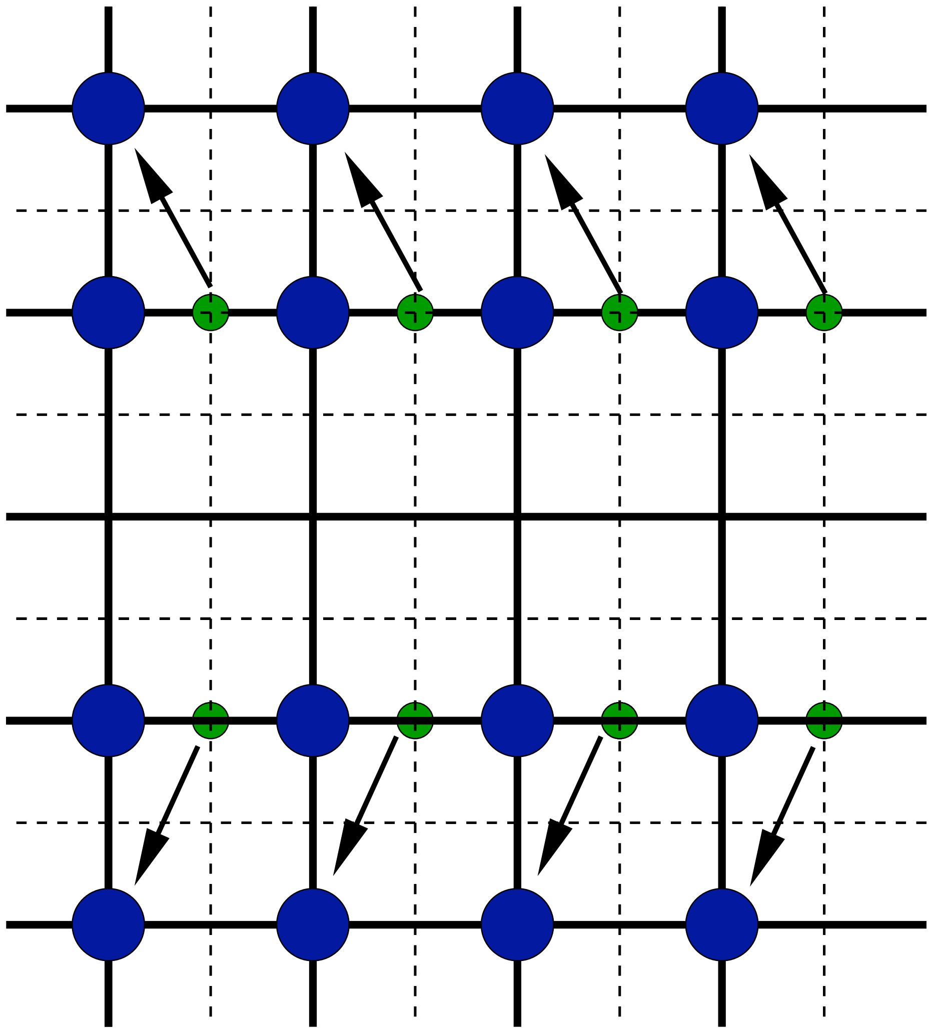
symmetries exact ⇒ eom not independent ⇒constraints (first class)

broken⇒ eom almost not independ. ⇒pseudo-constraints

Obtaining anomaly free constraints is equivalent to constructing an action with exact symmetries.

Boundary data for non-local actions

[Banisch, BD: to appear]



Boundary data for non-local actions

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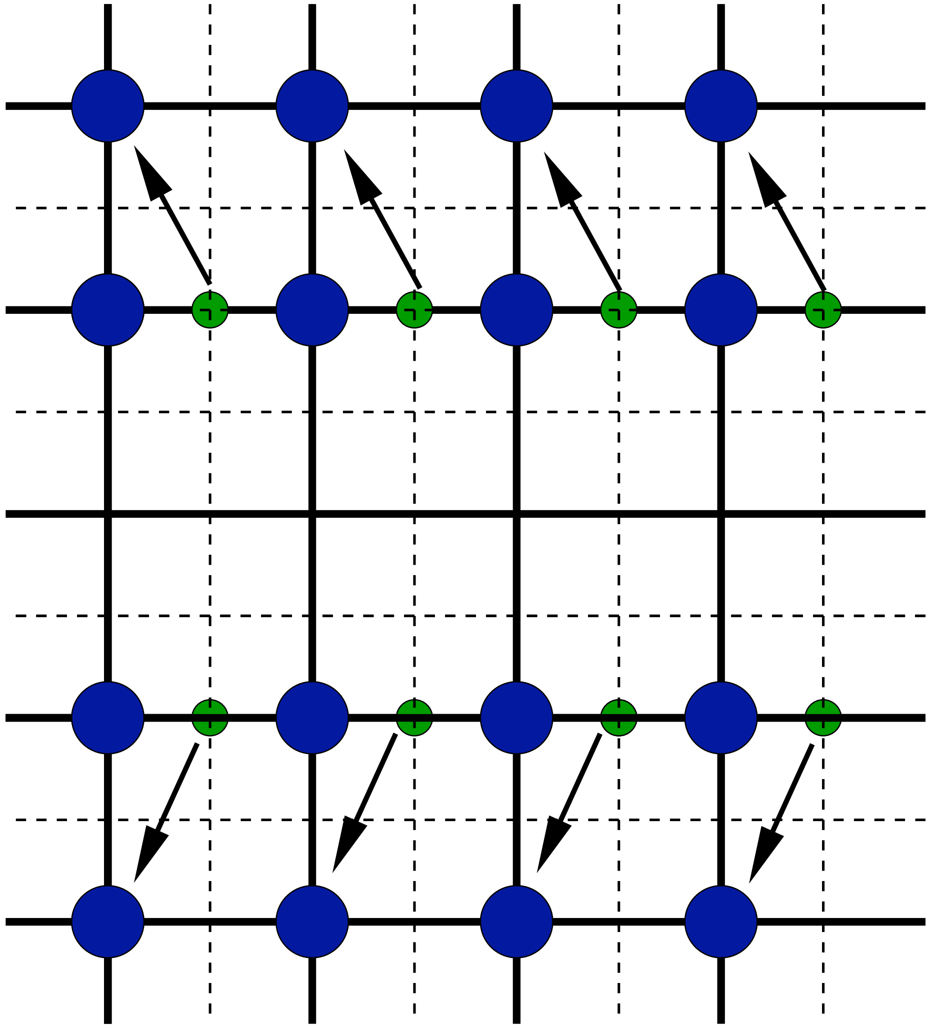


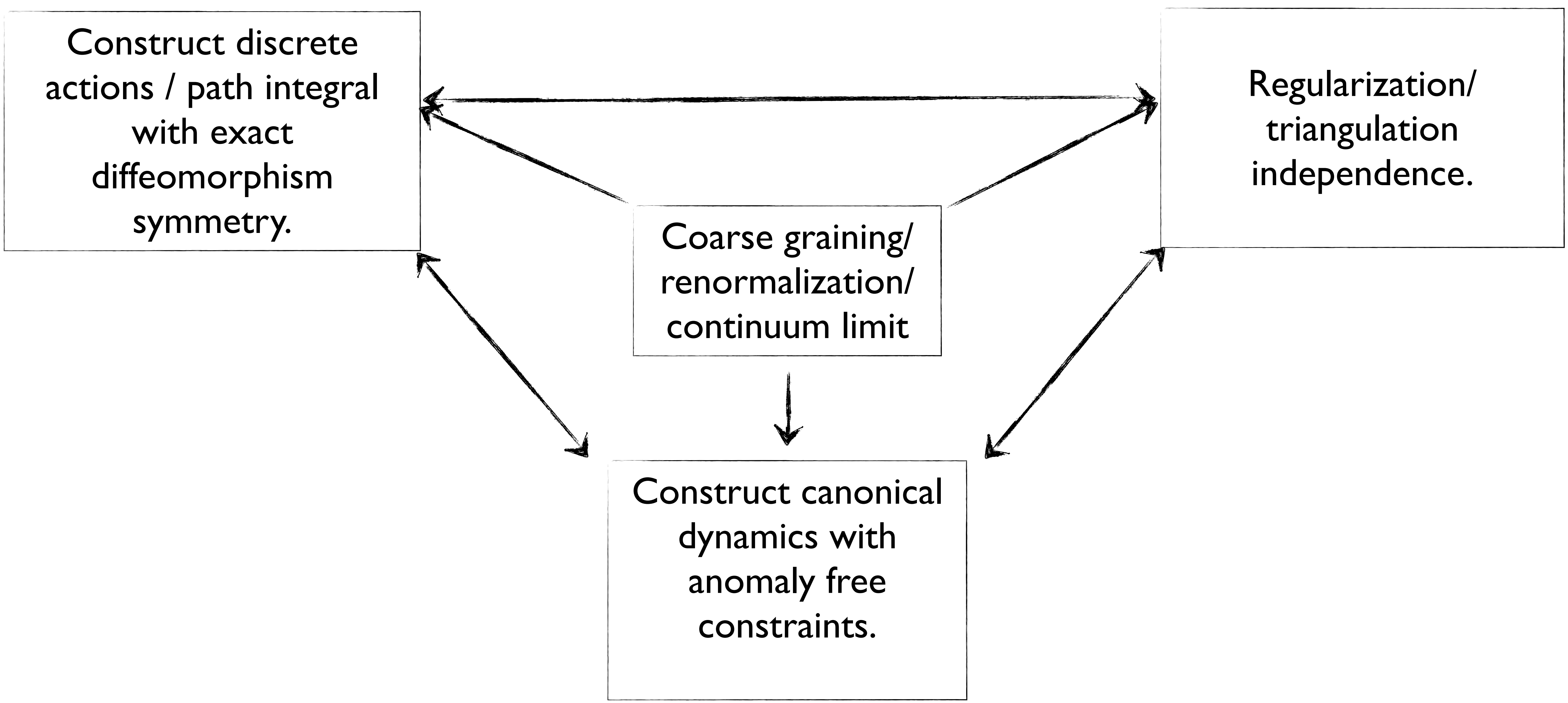
- non-local action lead to enlarged phase space
- interpretation?
- data specifying solution (on finer lattice) are distributed over 'thicker' boundaries

- phase space = space of solutions
- on finer lattice there are more solutions (modes) (exception: topological theories, 2d massless on regular square lattice)

- anomaly-free Hamiltonian constraints will be non-local

- rethink concept of boundary (carrying boundary data)

Main Message



- requiring diffeomorphism symmetry is a very strong principle
- diffeomorphism symmetry $\Rightarrow$ triangulation independence $\Rightarrow$ unique model?
- can be constructed via renormalization/coarse graining, which also gives information about large scale physics
- thus bring some of the main problems of the field together (discretization independence, Hamiltonian constraints, large scale limit)
- renormalization group approach allows for approximations and classification of relevant, irrelevant couplings
- have to understand better interplay between (broken/restored) diffeomorphism invariance, renormalization group flow, fixed point conditions

Summary

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- diffeomorphism symmetry ⇒ triangulation independence ⇒ unique model?
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- define coarse graining maps for classical and quantum mechanical models, develop approximations/ truncations

- perturbative improvement of actions and models: relation to numerical relativity

- relation to Ward identities (in gft) [Aristide]

- fixing ambiguities: path integral measure [BD, Steinhaus wip]

- canonical formalism with non-local actions and parametrized field theories: anomaly free Dirac (hypersurface deformation) algebra [Banisch, BD wip]

- coarse graining in spin foams [Bahr, BD, Eckert, Ryan wip]

Outlook

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dziekuje!