Quantum Field Theory on a Highly Symmetric Lattice

Marco Aliberti

Università degli Studi di Torino

23rd October, 2023

Matter is made of Atoms

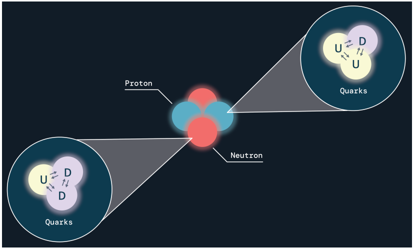

Image credits: NASA[NASA, 2022]

The Strong Interaction

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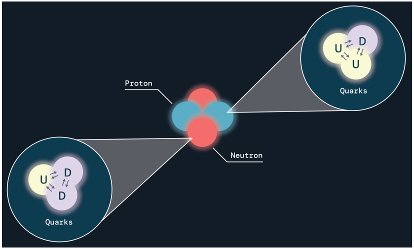
Atoms are made of Nuclei and Electrons



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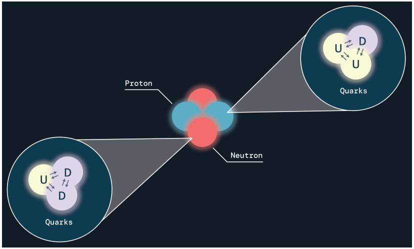

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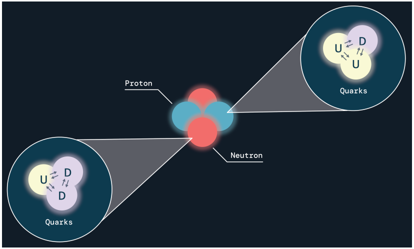

Quarks and Gluons

Described by Quantum Chromodynamics (QCD)

Image credits: NASA[NASA, 2022]

Quantum Chromodynamics (QCD)

Described by an $SU(3)$ Yang-Mills theory

$$S = \frac{1}{4}\int \mathrm{d}^4 x F^a_{\mu\nu}(x) F^{a\mu\nu}(x)$$

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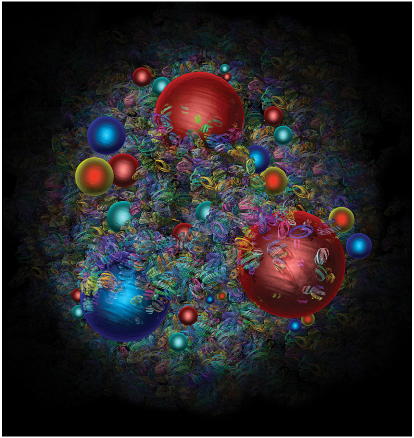

Figure: An artist's representation of a proton[CERN, 2019].

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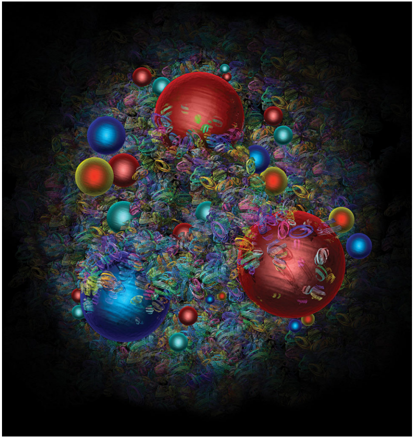

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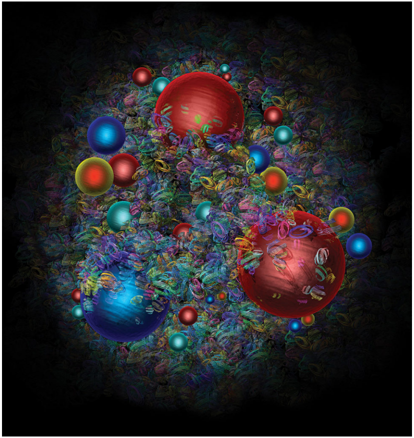
- Interesting purely-gluonic physics



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- Interesting purely-gluonic physics
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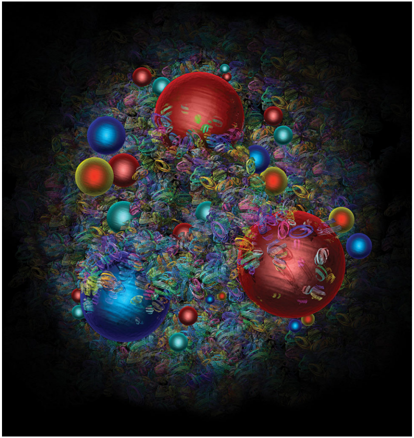

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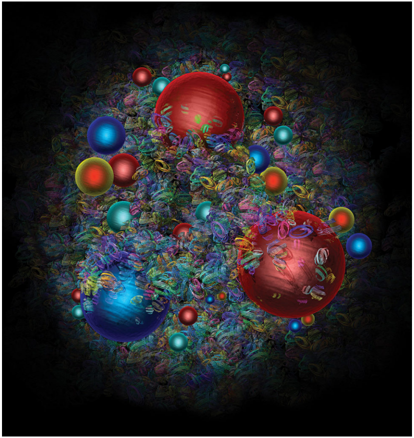
Lattice Field Theory



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What is a Lattice?

Definition: Lattice Λ

$\Lambda = \{\sum_{i=1}^{n} a_i e_i \mid a_i \in \mathbb{Z}\}$, with $\{e_i\}$ any basis of $\mathbb{R}^n$

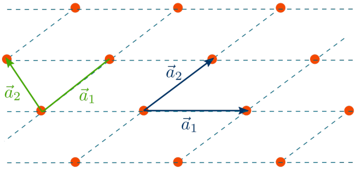

Figure: A bidimensional lattice.

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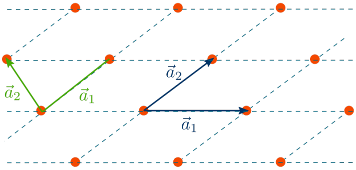

Figure: A bidimensional lattice.

Hypercubic lattice

$\{e_i\}$ is the canonical basis of $\mathbb{R}^n$
a is called *lattice spacing*.

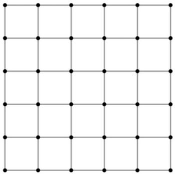

Figure: A square lattice.

Basic idea

Fields can take values only in given parts of the lattice, $x \to n \in \Lambda$.

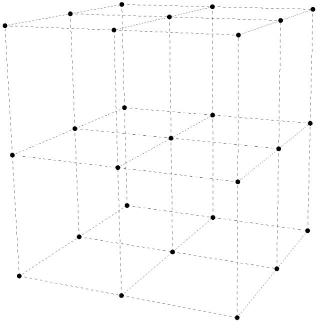

Figure: A (hyper)cubic lattice in $\mathbb{R}^3$.

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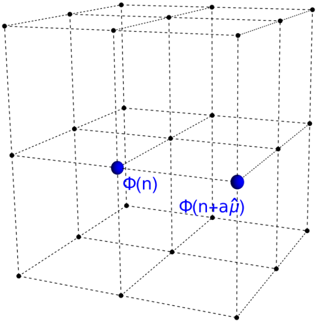
Examples:

- Scalar fields $\Phi(x) \to \Phi(n)$ on sites



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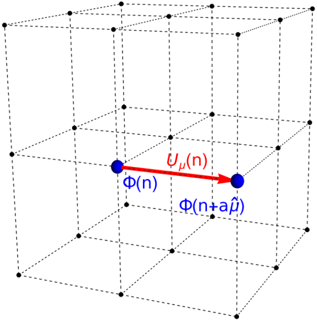
Parallel Transporter

$$U_\mu(x) = \exp(igaA_\mu(x))$$



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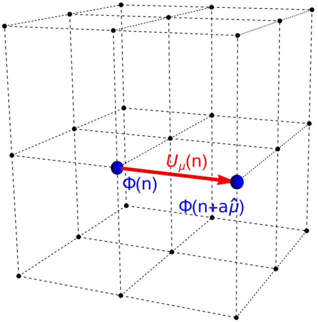

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Beware!

Spinorial fields are trickier to be discretized.

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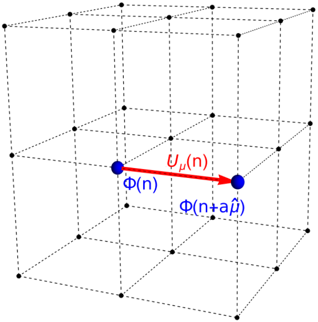

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Gauge-Invariant Observables and Wilson Action

The Yang-Mills continuum action is $S_E = \frac{1}{4}\int \mathrm{d}^4 x F^{a\mu\nu}(x) F^a_{\mu\nu}(x)$.

On the lattice, every closed path is gauge-invariant.

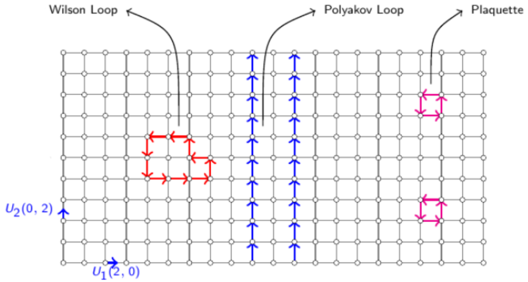

Figure: Gauge-invariant paths on a bidimensional lattice[Sigdel, 2016].

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$U_\mu(n)U_\nu(n+\mu)U^\dagger_\mu(n+\nu)U^\dagger_\nu(n)$

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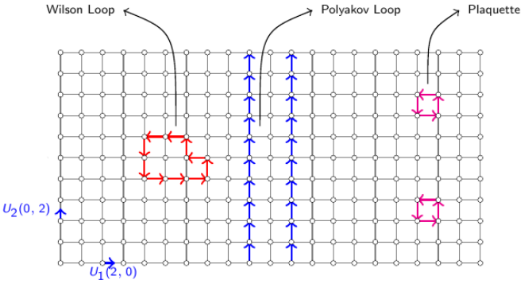

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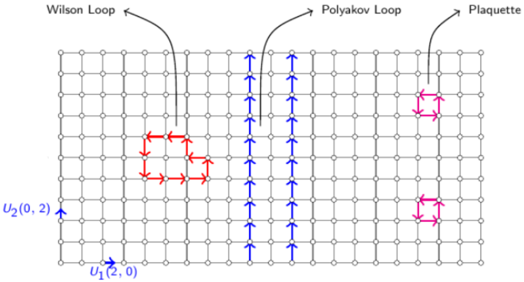
Wilson's Idea

$$S = \frac{\beta}{2N}\sum_{n,\mu,\nu} \mathfrak{Re}\,\mathrm{Tr}\left(\mathbb{1} - U_{\mu\nu}(n)\right)$$



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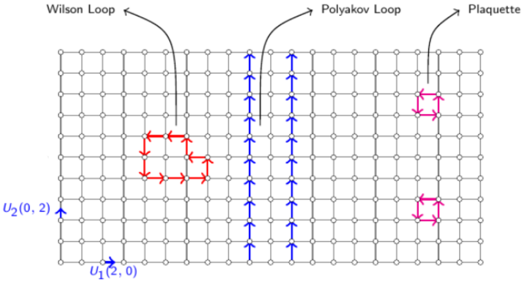
Polyakov Loops and Potential

If the time coordinate is taken to be periodic, more closed paths arise.

Polyakov Loop

$$P(n) = \mathrm{Tr} \prod_{t=0}^{T-1} U_t(n)$$



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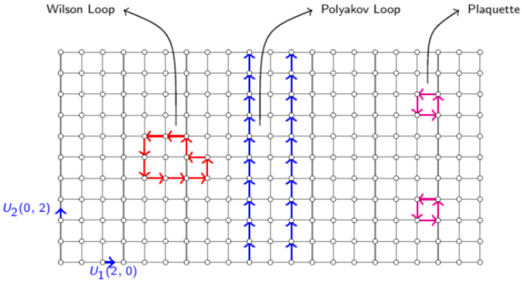
The expectation value of two Polyakov loops is the potential.

Polyakov Loop

$$P(n) = \mathrm{Tr} \prod_{t=0}^{T-1} U_t(n)$$

Potential

$$V(R) = -\frac{1}{T} \log < P(0)P^{\dagger}(R) >$$



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Monte Carlo Simulations

Computers are used to simulate Lattice Field Theories

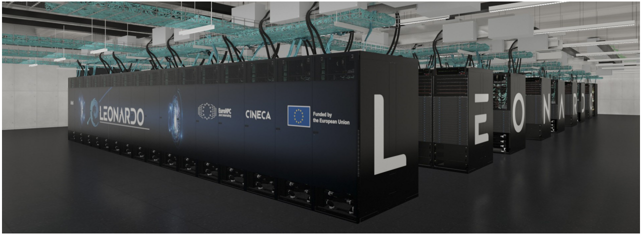

Figure: A rendering of the CINECA Leonardo supercomputer[Wikipedia, 2022].

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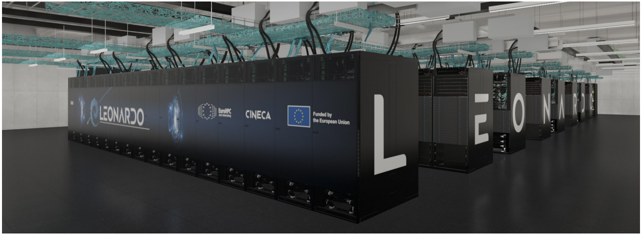

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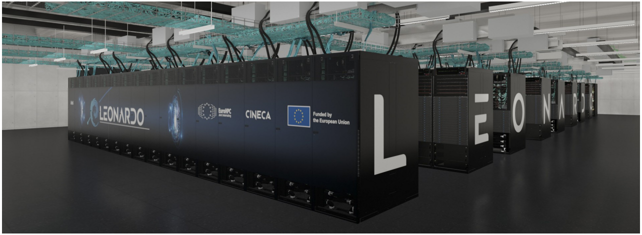

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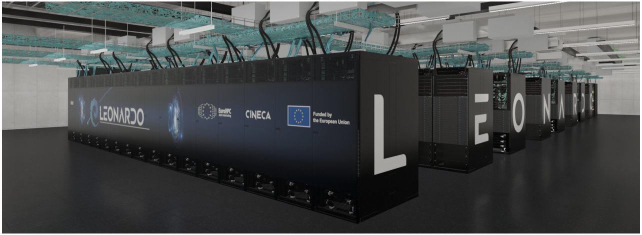
- A great number of observables is evaluated and then their mean value is computed.



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Translations

Rotations

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$$n \rightarrow \Gamma n \quad \Gamma \in G_{\Lambda_{SH}}$$

$G_{\Lambda_{SH}}$: group of rotations of multiples of 90° around any axis.

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Important:

Rotational invariance seems to be broken.

Rotational Invariance Restoration - Lang and Rebbi

Equipotential surfaces become spheres as the continuum limit is approached[Lang and Rebbi, 1982].
The gauge group used was the discrete icosahedral subgroup $\tilde{Y} \subset SU(2)$.

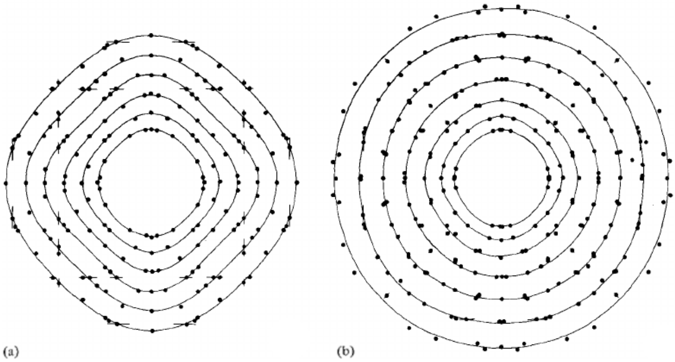

Figure: Restoration of rotational invariance from (a) $\beta = 2$, $n_s = 8$, $n_t = 4$ to (b) $\beta = 2.25$, $n_s = 16$, $n_t = 6$; the curves represent equipotential curves.

Rotational Invariance Restoration

Results of simulations for gauge group $SU(2)$ with 20000 measurements each[1]. Approach slightly different than Lang and Rebbi's.

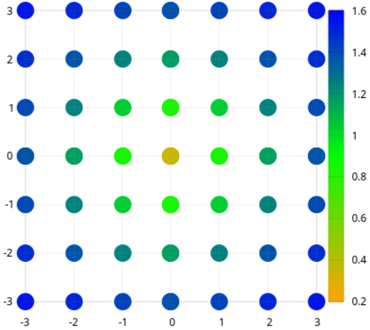

Figure: Potential from $\beta = 2.20$, $n_s = 8$, $n_t = 4$.

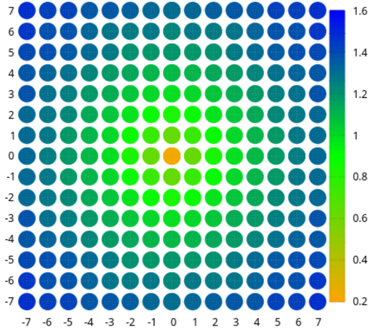

Figure: Potential from $\beta = 2.35$, $n_s = 16$, $n_t = 6$.

[1] The simulation code is based on the code presented in refs. [Panero, 2009; Mykkänen, Panero, and Rummukainen, 2012].

Higher Symmetry Lattices

Other, more rotational-symmetric, lattices have been used:

Body Centered Tesseract

- 24 nearest neighbours
- 1152-element symmetry group

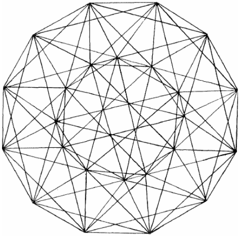

Figure: Two-dimensional projection of a BCT[Celmaster, 1982].

The SH lattice has 8 nearest neighbours and a 384-element symmetry group.

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F_4 coroots lattice[Neuberger, 1987]

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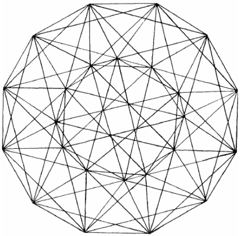

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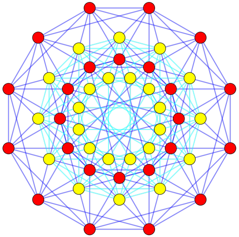

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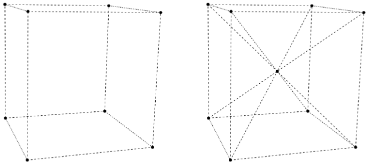

Figure: Cubic Cell (left) and BC Cubic Cell (right).

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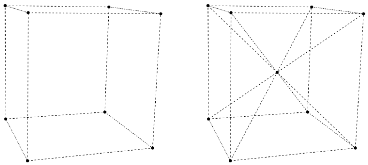

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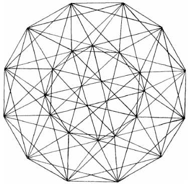

Figure: Bidimensional projection of the 24-cell.

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  - The 8 possible permutations of $(\pm 1, 0, 0, 0)$
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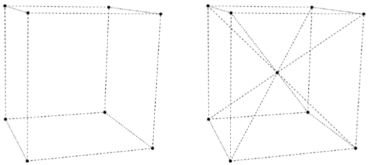

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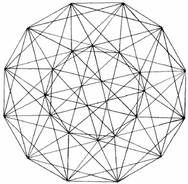

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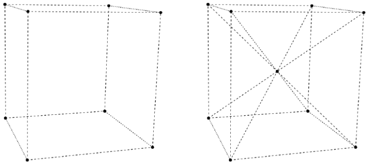
- Plaquettes are triangular;



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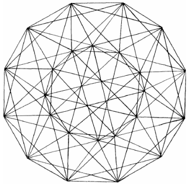

Figure: Bidimensional projection of the 24-cell.

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- Obtained from Simple Hypercubic lattice considering also the centers;
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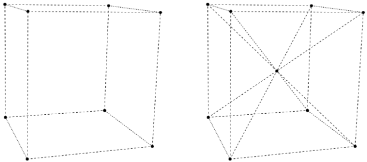

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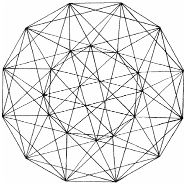

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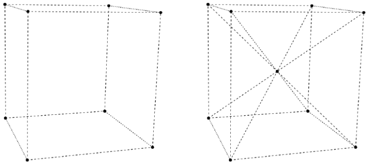

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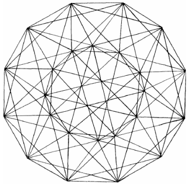

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F_4 Coroots Lattice

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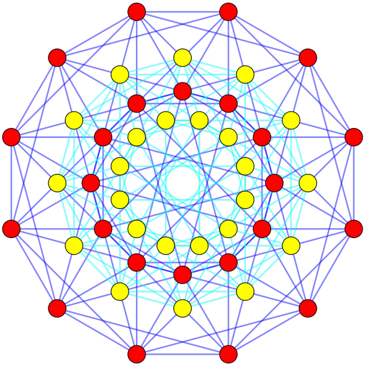

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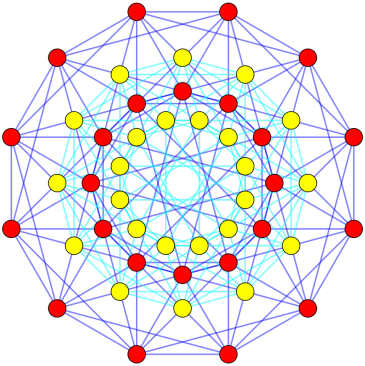

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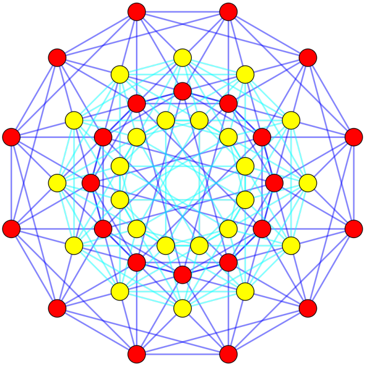

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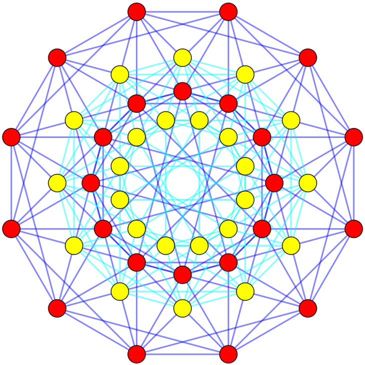

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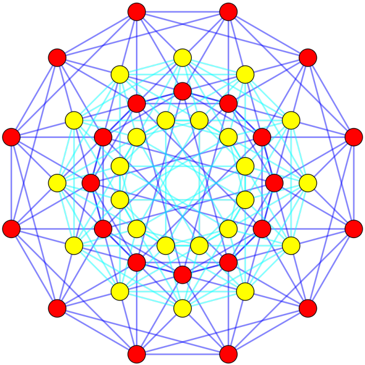

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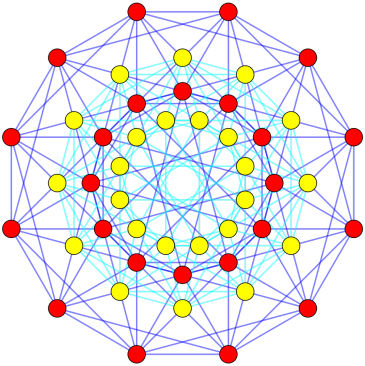

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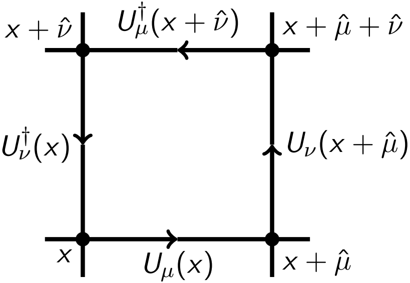
Simulations on SH Lattice

Wilson Action:

$$S_W = \frac{\beta}{2N} \sum_{x \in \Lambda} \sum_{\mu < \nu} \mathfrak{Re}\, \mathrm{Tr}[\mathbb{1} - U_{\mu\nu}(x)]$$

Plaquette:

$$U_{\mu\nu} = U_\mu(x) U_\nu(x+\hat{\mu}) U^\dagger_\mu(x+\hat{\nu}) U^\dagger_\nu(x)$$



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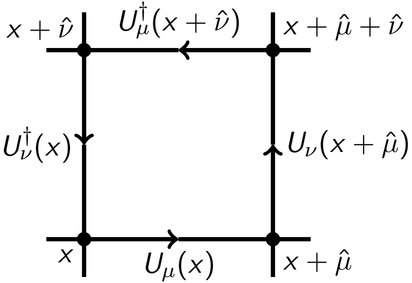
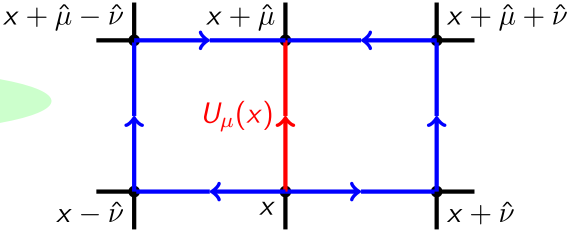


6 staples for each link



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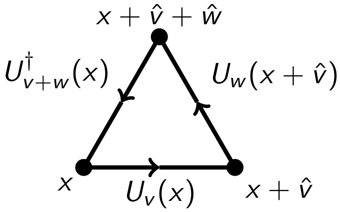

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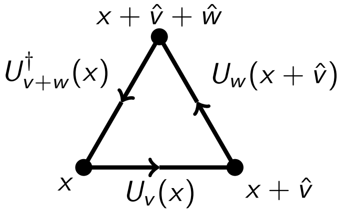
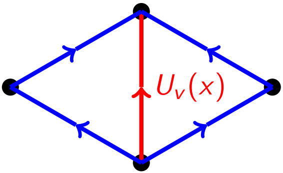


8 staples for each link



Average Plaquette as a function of Computer Time

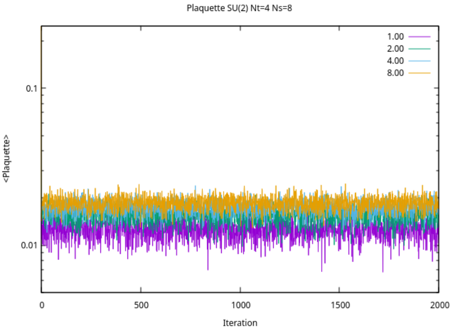


Figure: Lattice with $n_t = 4,\ n_s = 8$.

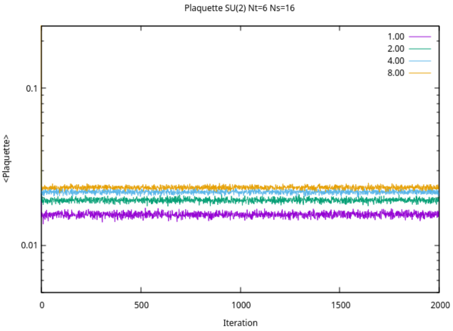
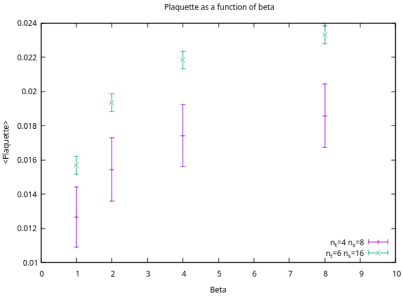


Figure: Lattice with $n_t = 6,\ n_s = 16$.

Simulation Results

Average Plaquette as a function of β



Purple data: $n_t = 4$, $n_s = 8$.
Green data: $n_t = 6$, $n_s = 16$.

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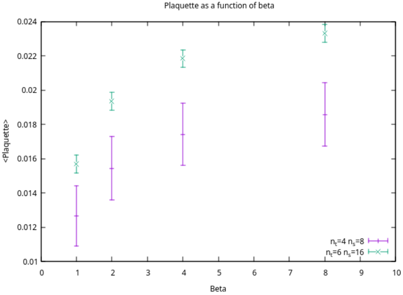

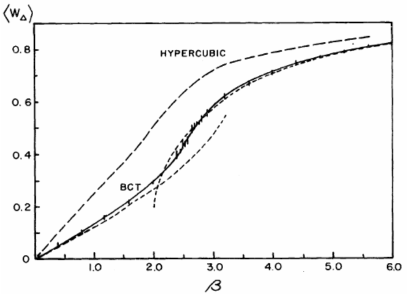

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Plot from [Celmaster, 1983].

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Thank you for your attention

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