

Title: PSI 2019/2020 - Quantum Field Theory II (David) - Lecture 13

Speakers: Francois David

Collection: PSI 2019/2020 - Quantum Field Theory II (David)

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Gauge Theories: Gauge Fixing

- o Gauge Fixing in Funcl. Integral
- o Teynman, B. DeWitt, Faddeev, Popov
F.D. Determinant
- o F.D. Ghosts Fields

ng

$$G = SU(2) , U(1)$$

egral

Gauge Field : Gauge Potential

, Popov

$$A_\mu$$

ng

egral

, Popov

$$G = SU(2) , U(1)$$

Gauge Field : Gauge Potential

$$A_\mu = A_\mu^a t_a \quad a=1,2,3$$

$\uparrow$ generator

$$G = SU(2) , U(1)$$

* Gauge Field : Gauge Potential

$$A_\mu = A_\mu^a t_a \quad a=1,2,3 \quad \text{Fundam Repr.}$$

$\uparrow$ generator $t_a = \frac{1}{2} \sigma_a \leftarrow \text{Pauli Matrices}$

2x2 matrix

* Gauge transformations

$$g = \{g(x), g \in SU(2)\}$$

$$g(x) = \mathbb{I} + i\alpha(x) \quad \alpha \in \text{Fund. Repr.}$$

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2x2 matrix

* Gauge transformations

$$g = \{g(x); g \in SU(2)\}$$

$$A_\mu \longrightarrow A_{g,\mu} = g(A_\mu + \partial_\mu)g^{-1}$$

$$g(x) = \mathbb{I} + i\alpha(x) \quad \alpha \in \text{Fund. Repr.} \quad A_\mu(x) \longrightarrow A_\mu(x) + \partial_\mu \alpha(x) - i[A_\mu(x), \alpha(x)]$$

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$$G = SU(2), U(1)$$

+ Gauge Field: Gauge Potential

$$A_\mu = A_\mu^a t_a \quad a=1,2,3 \quad \text{Fundam. Rep.}$$

2x2 matrices $t_a = \frac{1}{2} \sigma_a \leftarrow \text{Pauli Matrices}$

* Gauge transformations

$$g = \{g(x), g \in SU(2)\}$$

$$U_g(x) = \mathbb{I} + i\alpha(x) \quad \alpha \in \text{Fund. Rep.}$$

$$A_\mu \rightarrow A_{g,\mu} = g(A_\mu + \partial_\mu)g^{-1}$$

$$A_\mu(x) \rightarrow A_\mu(x) + \partial_\mu \alpha(x) - i[A_\mu(x), \alpha(x)] = A_\mu(x) + \overset{\text{covariant derivative}}{D_\mu} \alpha(x)$$

Action

Field Strength

$$S[A] = -\frac{1}{2g^2} \int d^4x \text{Tr} [F_{\mu\nu}(x) F^{\mu\nu}(x)]$$

$$F_{\mu\nu}(x) = \partial_\mu A_\nu - \partial_\nu A_\mu - i[A_\mu, A_\nu]$$

1)

Action

$$S[A] = -\frac{1}{2g^2} \int d^4x \text{Tr}[F_{\mu\nu}(x) F^{\mu\nu}(x)]$$

Field Strength

$$F_{\mu\nu}(x) = \partial_\mu A_\nu - \partial_\nu A_\mu - i[A_\mu, A_\nu]$$

2,3 Fundam Repr.

$\frac{1}{2}\sigma_a \leftarrow$ Pauli Matrices

$$A_\mu \longrightarrow A_{g,\mu} = g(A_\mu + \partial_\mu)g^{-1}$$

covariant derivative

Repr $A_\mu(x) \longrightarrow A_\mu(x) + \partial_\mu \alpha(x) - i[A_\mu(x), \alpha(x)] = A_\mu(x) + \overset{\text{covariant derivative}}{D}_\mu \alpha(x)$

Functional Integral (Feynman, ...)

$$\int \mathcal{D}[A] \exp\left(\frac{i}{\hbar} S[A]\right)$$

$$\mathcal{D}[A] = \prod_x \prod_{\mu=0}^3 \prod_{a=1}^3 dA_{\mu}^a(x)$$

Gauge Inv $S[A_g]$

Functional Integral (Feynman, ...)

$$\int \mathcal{D}[A] \exp\left(\frac{i}{\hbar} S[A]\right)$$

$$\mathcal{D}[A] = \prod_x \prod_{\mu=0}^3 \prod_{a=1}^3 dA_{\mu}^a(x)$$

↑ Huge Overcounting

↓ gauge Fixing procedure

Gauge Inv $S[A_g] = S[A]$

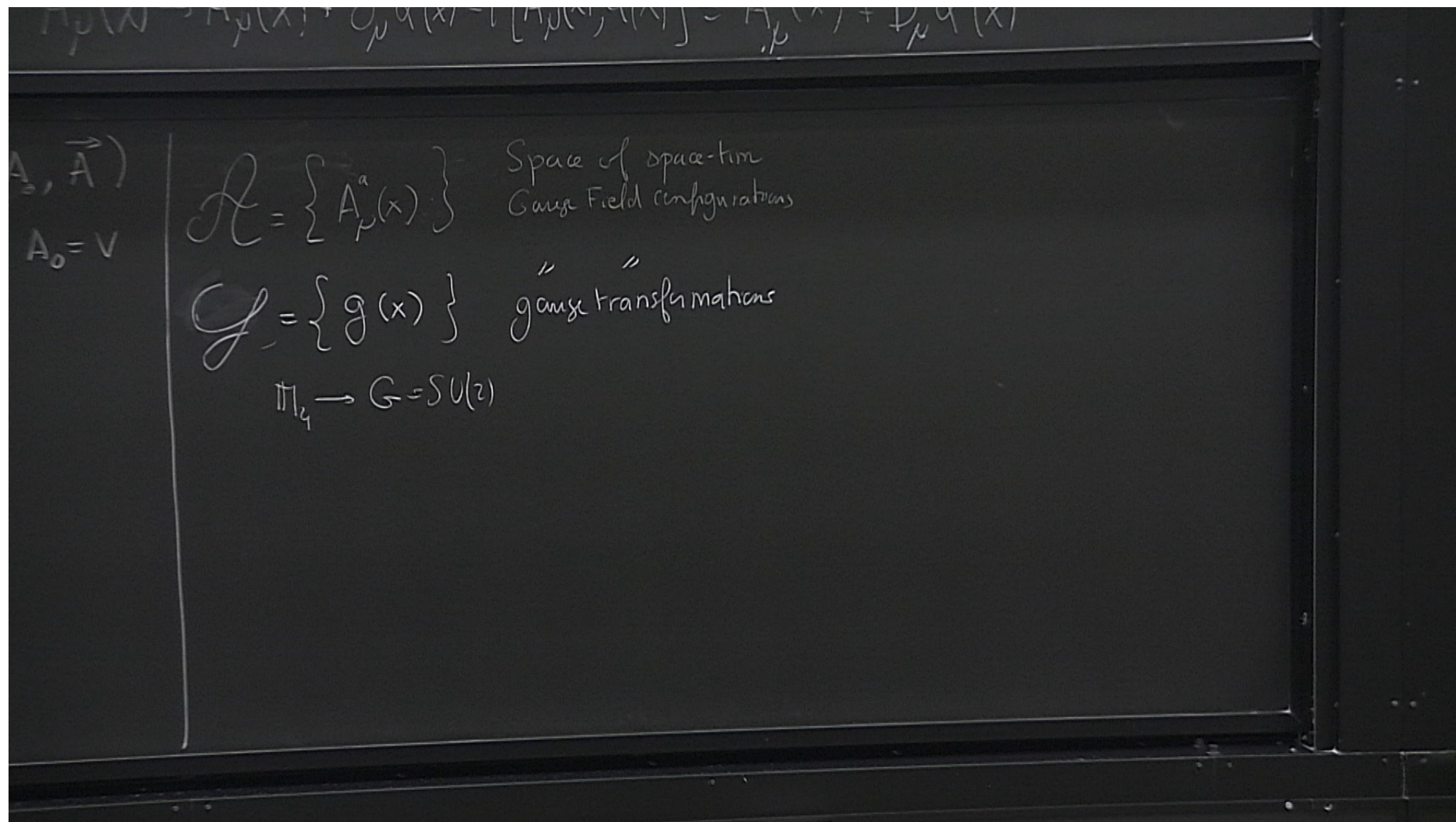
Example of gauge fi
Coulomb Gauge

Example of gauge fixing $A = (A_0, \vec{A})$

Coulomb Gauge $\vec{\nabla} \cdot \vec{A} = 0$ $A_0 = V$

Axial Gauge $A_0 = 0$

Lorentz Gauge $\partial^\mu A_\mu = 0$



$$\mathcal{R} = \{ A_\mu^a(x) \}$$

Space of space-time
Gauge Field configurations

$$\mathcal{G} = \{ g(x) \}$$

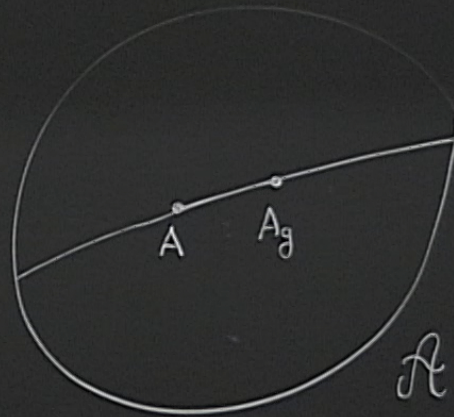
"gauge transformations"

$$\mathbb{M}_4 \rightarrow G = SU(2)$$

$\mathcal{G}$ Acts on $\mathcal{A}$

$$g: A \rightarrow A_g$$

$$\text{Orbit of } G = \{ A_g : g \in \mathcal{G} \text{ for a given } A \} = \text{"A physical configuration"}$$



$$g(x) = e^{i\alpha(x)} = 1 + i\alpha(x) + \dots$$

Definition of a (non-infinitesimal)
gauge transE

$$\begin{array}{ll} \phi_F \in \text{Fundamental Repr} & \phi_F \rightarrow g \cdot \phi_F = \phi_F g \\ \phi_A \in \text{Adjoint Repr} & \phi_A \rightarrow g \phi_A g^{-1} = \phi_A g \end{array}$$

D_μ is such that $\Leftarrow$ Covariant derivative

$$(D_\mu \phi)_g = D_\mu (\phi_g)$$

$$\mathcal{R} = \{ A_\mu^a(x) \}$$

Space of space-time
Gauge Field configurations

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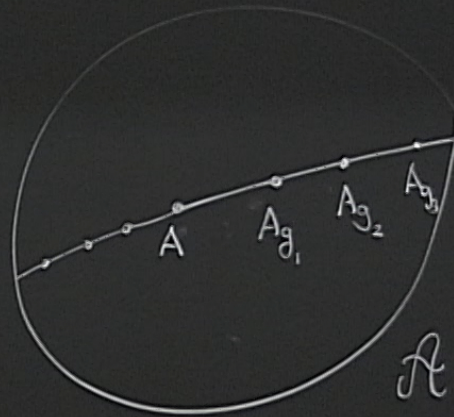
"gauge transformations"

$$M_4 \rightarrow G = SU(2)$$

$\mathcal{G}$ Action on $\mathcal{R}$

$$g: A \rightarrow A_g$$

Orbit of $A = \{ A_g : g \in \mathcal{G} \text{ for a given } A \} = \text{"A physical configuration"}$
under the action of G



$$\mathcal{R} = \{ A_\mu^a(x) \}$$

Space of space-time
Gauge Field configurations

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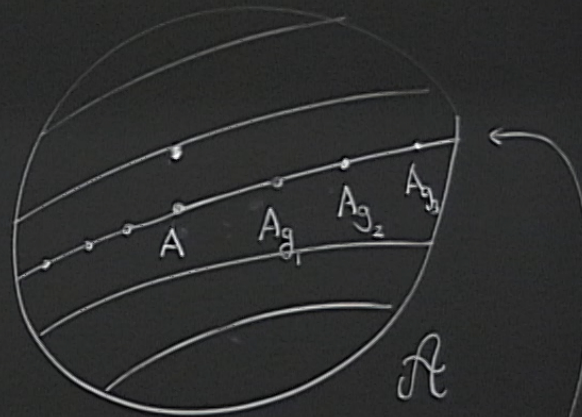
$$M_4 \rightarrow G = SU(2)$$

$\mathcal{G}$ Action of

$$g: A \rightarrow A_g$$

Orbit of $A = \{ A_g : g \in \mathcal{G} \text{ for a given } A \} = \text{"A physical configuration"}$
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$$G(A) = \{ A_g \}$$



$$\begin{array}{ll} g_1 & A \rightarrow A_{g_1} \\ g_2 & A \rightarrow A_{g_2} \\ & \text{etc.} \end{array} \quad \begin{array}{l} G \text{ is a group} \\ A_{gh} = (A_h)_g \end{array}$$

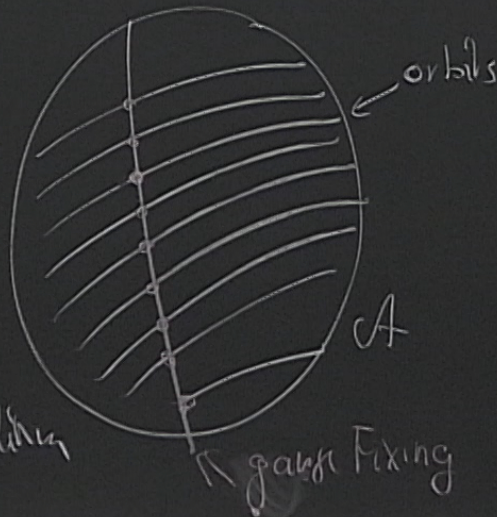
$\{\text{Physical Configurations}\} = \mathcal{A}/G = \text{Set of orbits}$
 quotient of $\mathcal{A}$ by the action of the group G

Gauge fixing

choose a "Gauge slice"

For each orbit, we have
a representative A in this slice

The A satisfies some gauge condition



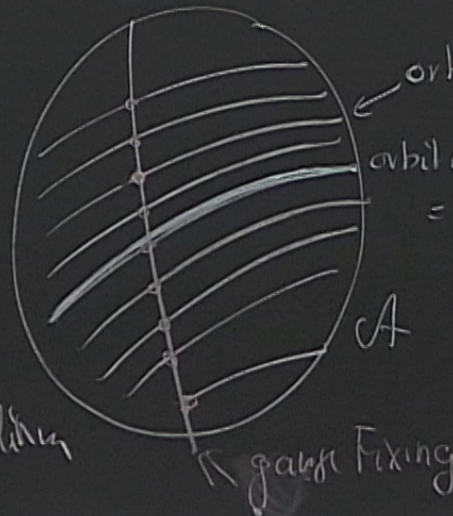
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orbits

orbit of the minimum of the action
 = ground state

$\mathcal{A}$

gauge fixing

$$S[A_0] = 0$$

$$F_{\mu\nu} = 0$$

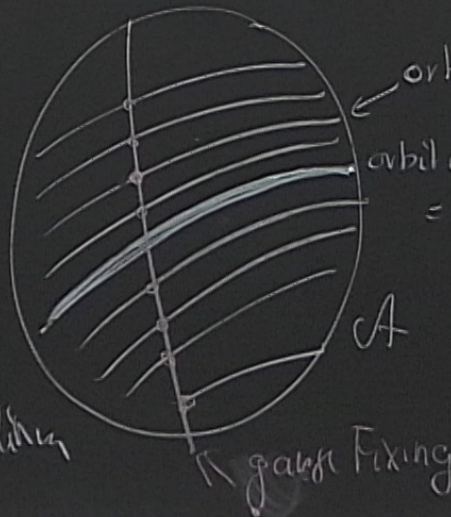
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Fully Quantum!

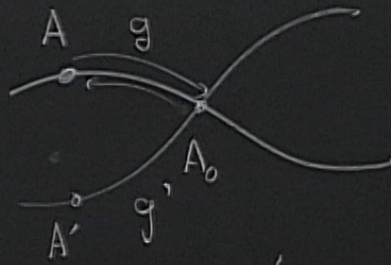
Definition of a (non-infinitesimal)

gauge transformation

$$\Phi \rightarrow g \Phi g^{-1} = \Phi_F g$$

$$\Phi \rightarrow g \Phi_A g^{-1} = \Phi_A g$$

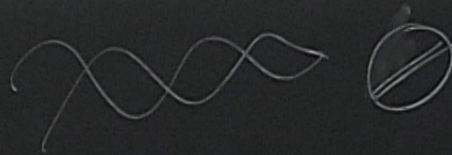
not derivative



$$A_g = A_0 = A'_g$$

$$A_{g \cdot h} = (A_h)_g \quad A = (A_0)g^{-1}$$

$$A' = A_{g'^{-1}g} \quad A' = (A_0)g'^{-1}$$



$$F_{\mu\nu} = 0 \Leftrightarrow \begin{aligned} E(t, \vec{x}) &= 0 \\ B(t, \vec{x}) &= 0 \end{aligned}$$

$U(1)$

$$A_\mu(t, \vec{x}) = 0$$

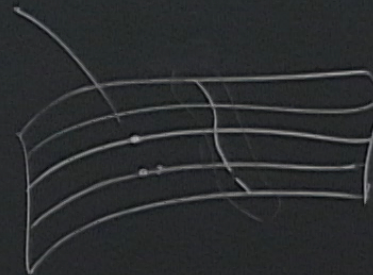
$\downarrow$ gauge

$$0 \neq A_\mu(t, \vec{x}) = \partial_\mu \alpha(t, \vec{x})$$

$\uparrow$ arbitrary

$$\{A_\mu(t, \vec{x})\}$$

$$g(x) - g(t, \vec{x})$$



$$G(A) = \{A_g\}$$

$$A \xrightarrow{g_2} A_{g_2}$$

Which 'measure' on each slice $\leftarrow$ gauge invariance

Trick. Write $\underline{1}$ as an integral

$$1 = \int dx \delta(x - x_0) = \int dx \delta(F(x)) |F'(x)|$$

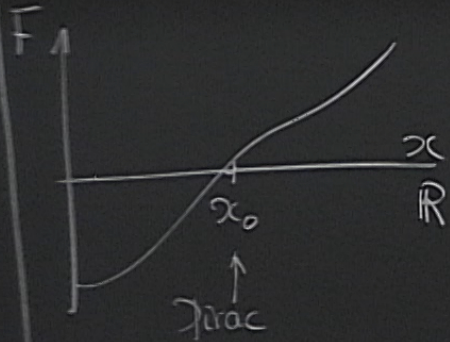
x_0 solution of $F(x_0) = 0 \leftarrow$ one solution $F'(x) = \frac{dF}{dx}(x)$
 $\uparrow$ function

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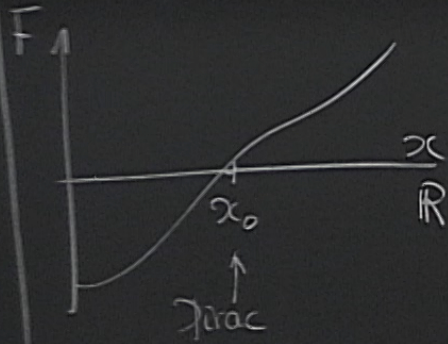
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change of variable $x \rightarrow F$

$$X = (x_1, \dots, x_n)$$

$$F(x) = (F_1(x), \dots, F_n(x))$$

n functions of n variables

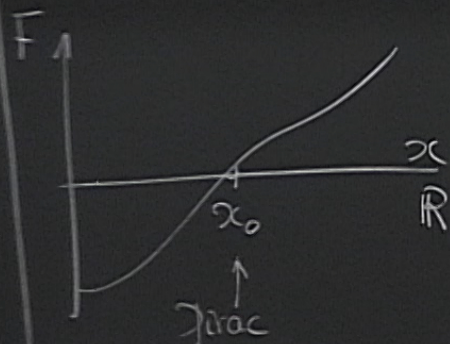
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change of variable $x \rightarrow F$ $\leftarrow$ function

$$\mathbb{R}^n \quad X = (x_1, \dots, x_n)$$

$$F(x) = (F_1(x), \dots, F_n(x)) ; F(X_0) = 0 \quad 1 \text{ solution}$$

n functions of n variables

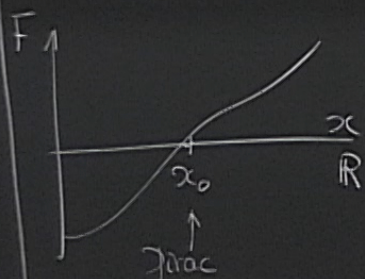
$$X_0$$

Orbit of $A = \{ A_g : g \in G; \text{ for a given } A \}$
 under the action of $G = \{ A_g \}$

G is a group
 $A \rightarrow A_{g_1}$
 $A \rightarrow A_{g_2}$
 etc...
 $A_{gh} = (A_h)_g$

Which "measure" on each slice $\leftarrow$ gauge invariance

Trick. Write 1 as an integral



$A_0 = 0$
 $= 0$

$$1 = \int dx \delta(x - x_0) = \int dx \delta(F(x)) |F'(x)|$$

x_0 solution of $F(x_0) = 0$ $\leftarrow$ one solution $F'(x) = \frac{dF}{dx}(x)$
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 change of variable $x \rightarrow F$

$\mathbb{R}^n$ $X = (x_1, \dots, x_n)$

x_0

$F(x) = (F_1(x), \dots, F_n(x))$; $F(X_0) = 0$ 1 solution
 in functions of n variables $X \rightarrow F$ $F_i(x) = 0$ is

$$1 = \int \delta^n[F(x)]$$

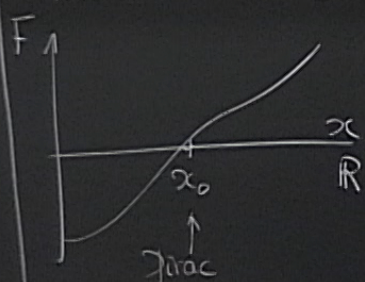
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Trick. Write 1 as an integral



$$1 = \int_{-\infty}^{\infty} \delta(F(x)) |F'(x)| dx$$

$$x_0 \text{ s.t. } F(x_0) = 0 \leftarrow \text{one solution } F'(x) = \frac{dF}{dx}(x)$$

$\leftarrow$ function
 $x \rightarrow F$

$$1 = \int dx \delta^{(n)}[F(x)]$$

$$\times \left| \det \left[\frac{\partial F_i(x)}{\partial x_j} \right] \right|$$

$$\text{matrix } \left\{ \frac{\partial F_i(x)}{\partial x_j} \right\}_{i,j=1,n}$$

Jacobian Matrix

$$\mathbb{R}^n \quad X = (x_1, \dots, x_n)$$

$$x_0$$

$$F_n(x); \quad F(X_0) = 0 \quad 1 \text{ solution}$$

$$X \rightarrow F \quad F_i(x) = 0 \quad i=1, n$$

$$1 = \int dx \delta(x - x_0)$$

$$= \int dx \prod_i \delta(F_i(x))$$

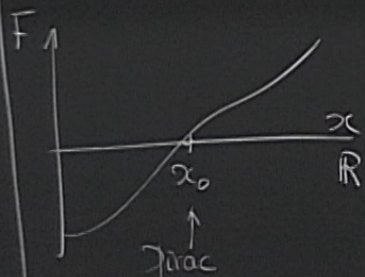
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x_0 solution of $F(x_0) = 0$ $\leftarrow$ one solution $F'(x) = \frac{dF}{dx}(x)$
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 change of variable $x \rightarrow F$

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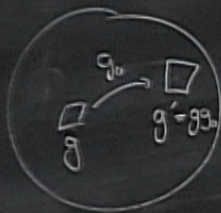
$$x_0$$

$F(x) = (F_1(x), \dots, F_n(x))$; $F(X_0) = 0$ 1 solution
 n functions of n variables $X \rightarrow F$ $F_i(x) = 0 \quad i=1, n$

$$1 = \int d^n x \delta(x - x_0)$$

$$= \int d^n x \prod_i \delta(F_i(x))$$

lie Group. $G = SU(2)$



Invariant

$$\int_G d\mu(g)$$

Haar measure
group invariant

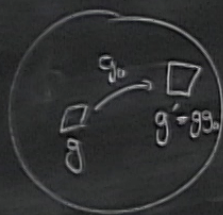
$$d\mu(g \cdot g_0) = d\mu(g) = d\mu(g_0 g)$$

lie Group: $G = SU(2)$

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Invariant



$$g_0 \in G$$

functions on $G \rightarrow \mathbb{R}$

$$F(g_0) = 0$$

$$1 = \int_G d\mu(g) \delta(g, g_0)$$

↑
group invariant Dirac Measure

Lie Group: $G = SU(2)$

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Haar measure
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invariant



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$$F(g_0) = 0$$

$$F = \{F^a; a=1, n\}$$

"dimension of the group"
dim of Lie algebra

$$1 = \int_G d\mu(g) \delta(g, g_0)$$

group invariant Dirac Measure

$$F(g) = F^a(g) \cdot t_a \quad G \rightarrow \text{Lie Alg. of } G$$

$\hat{=}$ generators

2×2 herm
traceless matrix

Lie Group: $G = SU(2)$

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2×2 herm.
traceless matrix

$\hat{=}$ generators

$$\delta F(g) = \prod_a \delta(F^a(g))$$

$$1 = \int_G d\mu(g) \delta[F(g)] \cdot |\det[F'(g)]|$$

$F'(g)$ $n \times n$ matrix

$$g \rightarrow g' = g(1 + i\alpha) \quad \alpha = \alpha^b t_b \in \text{Lie algebra}$$

$\uparrow$ real number $b=1,3$

$$\left. \frac{\partial F^a(g(1+i\alpha))}{\partial \alpha^b} \right|_{\alpha=0}$$

g fixed α^b are infinitesimal variable

$$1 = \int_G d\mu(g) \delta[F(g)] \cdot |\det[F'(g)]|$$

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$\uparrow$
real number $b=1, 3$

$$\left. \frac{\partial F^a(g(1+i\alpha))}{\partial \alpha^b} \right|_{\alpha=0} = \partial_b F^a(g)$$

g fixed α^b are infinitesimal variable

$$F'(g) = \left(\partial_b F^a(g) \right)$$

$\uparrow$ $n \times n$ matrix
real function
 $G \rightarrow \mathbb{R}$

$$F' : G \rightarrow \text{Mat}(n, \mathbb{R})$$

$G \rightarrow \text{Lie Algs of } G$

matrices

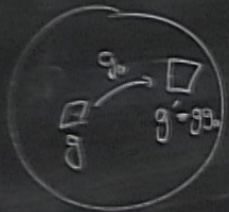
$g()$

Lie Group. $G = SU(2)$

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Haar Measure
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group invariant

Gauge Fixing Condition

$$\mathcal{F}[A] = 0$$

↑
gauge fixing

$$x, a \quad F^a(x; A) = \partial_\mu A^a_\mu(x) = 0$$

$$\mathcal{F} = \{ F^a(x; A) \}$$

↑
variable : function $M_4 \rightarrow$ Lie algebra
 x, a are the
indices $i = 1, n$

Gauge Fixing Condition

$$\mathcal{F}[A] = 0$$

gauge fixing

$$\mathcal{A} \rightarrow \text{Lie Algebra} \otimes M_4$$

$$M_4 \rightarrow \text{Lie Algebra}$$

$$x, a \quad F^a(x; A) = \partial_\mu A^a_\mu(x) = 0$$

$$\mathcal{F} = \{ F^a(x; A) \}$$

x, a are the indices $i=1, n$

$\uparrow$ variable : function $M_4 \rightarrow \text{Lie algebra}$

$$\int_A D[A] \quad \delta[F[A]]$$

$\int_A$ Big Functional
Integral

$\delta[F[A]]$ Big Dirac
Functional functional

$$\int_A D[A] \cdot \delta[F[A]] \times |\det[?]|$$

$\int_A$ Big Functional Integral
 $\delta[F[A]]$ Rig Dirac Functional function
 $|\det[?]|$

$$\int_A D[A] \cdot \delta[F[A]] \times |\det[\text{?}]| \quad \text{works?}$$

$\int_A$ Big Functional Integral
 $\delta[F[A]]$ Big Dirac Functional function
 $|\det[\text{?}]|$ F.P. determinant

group invariant Dirac Measure

Gauge Fixing Condition

$$\mathcal{F}[A] = 0$$

Gauge fixing

$$\mathcal{A} \rightarrow \text{Lie Algebra} \otimes M_4$$

$M_4 \rightarrow \text{Lie Algebra}$

$$A = \{A_\mu^a(x)\}$$

$$x, a \quad F^a(x; A) = \partial_\mu A_\nu^a(x) - \partial_\nu A_\mu^a(x) = 0$$

$$\mathcal{F} = \{F^a(x; A)\}$$

x, a are the indices $i = 1, n$

variable : function $M_4 \rightarrow \text{Lie algebra}$

$$\int \mathcal{D}[A]$$

Big Functional Integral

group invariant Dirac Measure

Gauge Fixing Condition

$$\mathcal{F}[A] = 0$$

Gauge fixing

$$x, a \quad F^a(x; A) = \partial^\mu A_\mu^a(x) = 0$$

$$\mathcal{F} = \{ F^a(x; A) \}$$

variable : function $M_4 \rightarrow \text{Lie algebra}$

$$A \rightarrow \left[\begin{array}{c} \text{Lie Algebra} \otimes M_4 \\ \hline M_4 \rightarrow \text{Lie Algebra} \end{array} \right]$$

x, a are the indices $i = 1, n$

$$A = \{ A_\mu^a(x) \} \rightarrow \{ F^a(x) \} \quad \text{function } M_4 \rightarrow \text{Lie Algebra}$$

$$\int_{\mathcal{A}} D[A] \cdot$$

Big Functional Integral

group invariant Dirac Measure

Gauge Fixing Condition

$$\mathcal{F}[A] = 0$$

gauge fixing

$$x, a \quad F^a(x; A) = \partial^\mu A_\mu^a(x) = 0$$

$$\mathcal{F} = \{ F^a(x; A) \}$$

variable : function $M_4 \rightarrow \text{Lie algebra}$

$$A \rightarrow \left[\begin{array}{c} \text{Lie Algebra} \otimes M_4 \\ \hline M_4 \rightarrow \text{Lie Algebra} \end{array} \right]$$

x, a are the indices $i=1, n$

$$A = \{ A_\mu^a(x) \} \rightarrow \{ F^a(x) \} \quad \text{function } M_4 \rightarrow \text{Lie Algebra} \quad F^a(x)|_a = F(x)$$

$$\int_{\mathcal{A}} D[A]$$

Big Function Integral