Gauge Fixing in a Spontaneously Broken Non-abelian Gauge Theory — ('t Hooft) R_ξ gauge

Working in Yang-Mills theory (gauge group, $\mathcal{G}$, consisting of multiple simple group factors), with scalars in various representations of $\mathcal{G}$.

— Convenient to put all scalars in the real representation, $\Phi_i(x)$ — This leads to factor of 2 of Casamir quadratics.

$\Rightarrow$ Then all generators, T^a_{ij}, are purely imaginary and antisymmetric in ij.

Gauge Transformation rule for $\Phi_i(x)$ (important for FP det.)

$$\Phi_i(x) \longrightarrow \left(\mathbb{1}_{ij} + i\alpha^a(x)\underbrace{T^a_{ij}}_{\text{Purely imaginary generators}}\right)\Phi_j(x)$$

$\alpha^a(x) \equiv$ parameters of transformation.

— Factor out a $-i$, to get real generators: $T^a = -i\underbrace{T^a_{Re}}_{\substack{\text{Purely real}\\ \text{(still antisymm.)}}}$

Then, $\Phi_i(x) \longrightarrow \left(\mathbb{1} + \alpha^a(x)T^a_{Re}\right)_{ij}\Phi_j(x)$ $\qquad [T^a_{Re}, T^b_{Re}] = -f^{abc}T^c_{Re}$

Then covariant derivatives become:

$$(D_\mu)_{ij}\,\Phi_j = \left(\delta_{ij}\partial_\mu + iA^a_\mu (gT^a)_{ij}\right)\Phi_j = \left(\delta_{ij}\partial_\mu + A^a_\mu (gT^a_{Re})_{ij}\right)\Phi_j$$

And gauge fields transform like:

$$A^a_\mu \longrightarrow A^a_\mu - \partial_\mu \frac{\alpha^a}{g} - f^{abc}\alpha^b A^c_\mu \equiv A^a_\mu - \left(D^{ab}_\mu \frac{\alpha^b}{g}\right), \quad \text{as usual.}$$

gauge covariant derivative in the adjoint rep:

$$D^{ab}_\mu = \partial_\mu \delta^{ab} + g f^{abc} A^c_\mu$$

n.b. $A^a_\mu \to A^a_\mu \oplus \partial_\mu \frac{\alpha^a}{g} \oplus f^{abc}\alpha^a A^c_\mu \equiv A^a_\mu + \underbrace{D^{ab}_\mu}_{\text{unchanged}} \frac{\alpha^b}{g}$
is used if $D_\mu = \partial_\mu \ominus iA^a_\mu (gT^a)_{ij}$

Lagrangian:

$$\mathcal{L} = \frac{1}{2}\underbrace{(D_\mu\Phi)}_{\text{expand}}(D^\mu\Phi) - \frac{1}{4}F^a_{\mu\nu}F^{\mu\nu a} - V(\Phi)$$

$$= \frac{1}{2}\left(\partial_\mu\Phi_i + A^a_\mu gT^a_{ij}\Phi_j\right)\left(\partial^\mu\Phi_i + A^{\mu b}gT^b_{ik}\Phi_k\right) \underbrace{- \frac{1}{4}F^a_{\mu\nu}F^{\mu\nu a}}_{\text{Now expand this.}} - V(\Phi)$$

Note: $F_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a - g f^{abc} A_\mu^b A_\nu^c$ for non-abelian gauge theories.

Then:

$$-\frac{1}{4}F_{\mu\nu}^a F^{\mu\nu a} = -\frac{1}{4}(\partial_\mu A_\nu^a - \partial_\nu A_\mu^a)(\partial^\mu A^{\nu a} - \partial^\nu A^{\mu a}) + \frac{1}{4}\times 2g\, f^{abc}(\partial_\mu A_\nu^a - \partial_\nu A_\mu^a)A^{\mu b}A^{\nu c}$$
$$- \frac{1}{4}g^2 f^{abc} f^{ade} A_\mu^b A_\nu^c A^{\mu d} A^{\nu e}$$

$$= \underbrace{-\frac{1}{2}\partial_\mu A_\nu^a (\partial^\mu A^{\nu a} - \partial^\nu A^{\mu a})}_{\text{Integrate by parts}} + \underbrace{g f^{abc}\partial_\mu A_\nu^a A^{\mu b} A^{\nu c}}_{\text{``}gA^3\text{''}}^{\text{Ⓐ}} - \underbrace{\frac{g^2}{4} f^{abc} f^{ade} A_\mu^b A_\nu^c A^{\mu d} A^{\nu e}}_{\text{``}g^2A^4\text{''}}^{\text{Ⓑ}}$$

$$= +\frac{1}{2}A_\nu^a(\partial_\mu\partial^\mu A^{\nu a} - \partial_\mu\partial^\nu A^{\mu a}) + \ldots$$

$$= \frac{1}{2}A_\mu^a(\partial^2 g^{\mu\nu} - \partial^\mu\partial^\nu)A_\nu^a + \text{``}gA^3\text{''} + \text{``}g^2A^4\text{''}.$$

Substitute back to obtain the Lagrangian:

$$\mathcal{L} = \frac{1}{2}\partial_\mu \Phi_i \partial^\mu \Phi_i + A^{\mu b}\partial_\mu \Phi_i\, gT_{ij}^b \Phi_j + \frac{1}{2}A_\mu^a A^{\mu b}(gT^a\Phi)_i(gT^b\Phi)_i - V(\Phi)$$
$$+ \frac{1}{2}A_\mu^a(\partial^2 g^{\mu\nu} - \partial^\mu\partial^\nu)A_\nu^a + gA^3 + g^2A^4.$$

Suppose Φ spontaneously acquires a nonzero vacuum expectation value in some of its components.

Write $\Phi_i(x) = \langle\phi\rangle_i + \phi_i(x)$
$$\begin{cases} \delta\phi_i(x) = \alpha^a T_{ij}^a(\langle\phi\rangle + \phi)_j \\ \delta\langle\phi\rangle_i = 0 \end{cases}$$

Divide* the space of values for $\phi_i(x)$ into two subspaces:

① The space spanned by (non-zero) directions $T^a\langle\phi\rangle_i$ ← a such vectors; i are these vectors' components
– field fluctuations in these directions are <u>eaten Goldstone bosons</u>.

② Space spanned by directions orthogonal to the $T^a\langle\phi\rangle_i$. (ie $T^a\langle\phi\rangle_i$ vanishes)
– field fluctuations in these directions are the <u>physical uneaten scalars</u>.

* [this division cannot be made if $\langle\phi\rangle$ doesn't minimize $V(\Phi)$]

- Shift: $\Phi \to \langle\phi\rangle + \phi$

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi_i\partial^\mu\phi_i + A^{\mu b}\partial_\mu\phi_i\, gT^b_{ij}\overset{\text{(C)}}{(\langle\phi\rangle+\phi)_j} + \frac{1}{2}A^a_\mu A^{\mu b}\overset{\text{(D)}}{\left(gT^a(\langle\phi\rangle+\phi)\right)_i}\overset{\text{(E)}}{\left(gT^b(\langle\phi\rangle+\phi)\right)_i}$$
$$- V(\langle\phi\rangle_i+\phi_i) + \frac{1}{2}A^a_\mu(\partial^2 g^{\mu\nu} - \partial^\mu\partial^\nu)A^a_\nu + gA^3 + g^2A^4.$$

Collect terms quadratic in fields (higher order in fields give rise to interactions, and are not relevant for now).

$$\mathcal{L}^{(\text{Quad})} = \overset{\text{(I)}}{\frac{1}{2}\partial_\mu\phi_i\partial^\mu\phi_i} \overbrace{+ A^{\mu a}\partial_\mu\phi_i[gT^a\langle\phi\rangle]_i}^{\partial_\mu A^\mu-\phi \text{ mixing term}} + \underbrace{\overset{\text{(VI)}}{\frac{1}{2}[gT^a\langle\phi\rangle]_i[gT^b\langle\phi\rangle]_i A^a_\mu A^b_\nu}}_{\text{Mass matrix for gauge fields.}}$$
$$-\frac{1}{2}\frac{\partial^2 V}{\partial\Phi_i\partial\Phi_j}\bigg|_{\Phi=\langle\phi\rangle}\phi_i\phi_j + \overset{\text{(IV)}}{\frac{1}{2}A^a_\mu(\partial^2 g^{\mu\nu} - \partial^\mu\partial^\nu)A^a_\nu}.$$

The second term, $A^{\mu a}\partial_\mu\phi_i[gT^a\langle\phi\rangle]_i$, mixes gauge bosons with goldstone bosons (for nonzero $gT^a\langle\phi\rangle$).

- When quantizing the system, $\mathcal{L}_{GF} = -\frac{1}{2\xi}(\mathcal{F}^a)^2$ is added.

Choose $\mathcal{F}^a = (\partial^\mu A^a_\mu - \xi[gT^a\langle\phi\rangle]_i\phi_i)$, ← 't Hooft gauge ($R_\xi$)

$$\mathcal{L}_{GF} = -\frac{1}{2\xi}(\partial^\mu A^a_\mu)^2 - \frac{\xi}{2}[gT^a\langle\phi\rangle]_i\phi_i[gT^a\langle\phi\rangle]_j\phi_j + \partial_\mu A^{\mu a}[gT^a\langle\phi\rangle]_i\phi_i$$
$$-\frac{1}{2\xi}\partial^\mu A^a_\mu\partial^\nu A^a_\nu$$

Integrate by parts   Integrate by parts.

$$= \underbrace{+\overset{\text{(V)}}{\frac{1}{2\xi}A^a_\mu\partial^\mu\partial^\nu A^a_\nu}}_{\substack{\text{Combines with gauge}\\ \text{boson kinetic term altering}\\ \text{vector boson propagator}}} \underbrace{\overset{\text{(III)}}{-\frac{\xi}{2}[gT^a\langle\phi\rangle]_i\phi_i[gT^a\langle\phi\rangle]_j\phi_j}}_{\substack{\text{Gives } \xi\text{-dep. masses to}\\ \text{goldstone bosons}}} \underbrace{- A^{\mu a}[gT^a\langle\phi\rangle]_i\partial_\mu\phi_i}_{\substack{\text{Cancels } \partial_\mu A^\mu-\phi\\ \text{mixing term.}}}$$

- Now, work on the compensating Fadeev-Popov determinant: need gauge transformed fixing condition.

$$\frac{\delta\mathcal{F}'}{\delta\alpha}$$

$$\mathcal{F}^a(\underbrace{A',\phi'}_{\text{gauge transformed}}) = \partial^\mu A'^a_\mu - \xi[gT^a\langle\phi\rangle]_i\phi'_i$$

These fields are gauge transformed with parameter $\alpha^a(x)$

$$\mathcal{F}^a(A',\phi') = \partial^\mu\Big(A_\mu - \overset{\partial_\mu + g f^{abc}\alpha^b A^c_\mu}{\overset{\downarrow}{D_\mu}}\,\frac{\alpha}{g}\Big)^a - \xi\big[gT^a\langle\phi\rangle\big]_i\big(\phi_i + \alpha^b T^b_{ij}(\langle\phi\rangle+\phi)_j\big)$$

$$= \partial^\mu A^a_\mu - \partial^\mu\partial_\mu \frac{\alpha^a}{g} - f^{abc}(\partial^\mu\alpha^b)A^c_\mu - f^{abc}\alpha^b(\partial^\mu A^c_\mu)$$

$$- \xi(gT^a\langle\phi\rangle)_i\,\phi_i - \xi(gT^a\langle\phi\rangle)_i\big(\alpha^b T^b_{ij}(\langle\phi\rangle+\phi)_j\big)$$

Now use $\dfrac{\delta\mathcal{F}'^a(x)}{\delta\alpha^b(y)} = \dfrac{\partial\mathcal{F}'^a}{\partial\alpha^b}\delta^4(x-y) + \dfrac{\partial\mathcal{F}'^a}{\partial(\partial^\mu\alpha^b)}\partial^\mu\delta^{(4)}(x-y) + \dfrac{\partial\mathcal{F}^a}{\partial(\partial^\mu\partial^\nu\alpha^b)}\partial^\mu\partial^\nu\delta^{(4)}(x-y)$

So,

$$\frac{\delta\mathcal{F}'^a(x)}{\delta\alpha^b(y)} = -f^{abc}(\partial^\mu A^c_\mu)\,\delta^{(4)}(x-y) - \xi(gT^a\langle\phi\rangle)_i T^b_{ij}(\langle\phi\rangle+\phi)_j\,\delta^{(4)}(x-y)$$

$$- f^{abc}A^c_\mu\,\partial^\mu\delta^{(4)}(x-y) - \frac{\delta^{ab}}{g}g_{\mu\nu}\,\partial^\mu\partial^\nu\delta^{(4)}(x-y)$$

$$= \Big[\underbrace{-\frac{\delta^{ab}}{g}\partial^2 - f^{abc}\,\partial^\mu A^c_\mu - f^{abc}A^c_\mu\,\partial^\mu}_{=\left(-\partial^\mu \frac{D^{ab}_\mu}{g}\right)}$$

$$- \xi(gT^a\langle\phi\rangle)_i T^b_{ij}(\langle\phi\rangle+\phi)_j\Big]\,\delta^{(4)}(x-y)$$

Then, $\det\left(\dfrac{\delta\mathcal{F}'^a(x)}{\delta\alpha^b(y)}\right) \longrightarrow \displaystyle\int \mathcal{D}\bar\eta\,\mathcal{D}\eta\; e^{i\int d^4x\left[-\bar\eta^a\left(\partial^\mu\frac{D_\mu}{g} + \xi(gT\langle\phi\rangle)T(\langle\phi\rangle+\phi)\right)\eta^b\right]}$

(missing steps shown in "Gauge Fixing" notes)

Hence, the ghost Lagrangian is:

$$\mathcal{L}_{Ghost} = -\bar\eta^a\Big[\frac{\delta^{ab}}{g}\partial^2 + f^{abc}\partial^\mu(A^c_\mu\,\cdot) + \xi(gT^a\langle\phi\rangle)_i\,T^b_{ij}(\langle\phi\rangle+\phi)_j\Big]\eta^b$$

$$= -\frac{1}{g}\bar\eta^a\Big[\delta^{ab}\partial^2 + g f^{abc}\partial^\mu(A^c_\mu\,\cdot) + \xi(gT^a\langle\phi\rangle)_i\,gT^b_{ij}(\langle\phi\rangle+\phi)_j\Big]\eta^b$$

absorb only $1/g^2$

Now integrate by parts in first two terms:

$$= \partial_\mu\bar\eta^a\partial^\mu\eta^a + g f^{abc}(\partial^\mu\bar\eta^a)\eta^b A^c_\mu - \xi\bar\eta^a\eta^b\big[gT^a\langle\phi\rangle\big]_i\big(gT^b_{ij}(\langle\phi\rangle+\phi)_j\big)$$

$$= \overset{\text{VII}}{\partial_\mu\bar\eta^a\partial^\mu\eta^a} + \overset{\text{F}}{g f^{abc}(\partial^\mu\bar\eta^a)\eta^b A^c_\mu} - \overset{\text{VIII}}{\xi\bar\eta^a\eta^b\big[gT^a\langle\phi\rangle\big]_i\big[gT^b\langle\phi\rangle\big]_i}$$

$$- \xi\bar\eta^a\eta^b\big[gT^a\langle\phi\rangle\big]_i\big(gT^b_{ij}\phi_j\big) \quad \text{G}$$

Hence, the full Lagrangian is: $\mathcal{L}_{YM+Scalar} + \mathcal{L}_{GF} + \mathcal{L}_{Ghost} = \mathcal{L}^{Quad} + \mathcal{L}^{Int}$

$$\mathcal{L}^{Quad} = \frac{1}{2}\phi_i\left(\overset{\text{I}}{-\partial^2\delta_{ij}} - \overset{\text{II}}{M^2_{ij}} - \overset{\text{III}}{\xi[gT^a\langle\phi\rangle]_i[gT^a\langle\phi\rangle]_j}\right)\phi_j$$

$$+\frac{1}{2}A^a_\mu\left(\overset{\text{IV}}{\partial^2 g^{\mu\nu}\delta^{ab}} - \overset{\text{V}}{\left(1-\frac{1}{\xi}\right)\partial^\mu\partial^\nu\delta^{ab}} + \overset{\text{VI}}{[gT^a\langle\phi\rangle]_i[gT^b\langle\phi\rangle]_i g^{\mu\nu}}\right)A^b_\nu$$

$$+\bar{\eta}^a\left(\overset{\text{VII}}{-\partial^2\delta^{ab}} - \overset{\text{VIII}}{\xi[gT^a\langle\phi\rangle]_i[gT^b\langle\phi\rangle]_i}\right)\eta^b$$

$$\mathcal{L}^{int} = \overset{\text{A}}{+gf^{abc}\partial_\mu A^a_\nu A^{\mu b}A^{\nu c}} - \overset{\text{B}}{\frac{g^2}{4}f^{abc}f^{ade}A^b_\mu A^c_\nu A^{\mu d}A^{\nu e}} + \left(\begin{array}{c}\text{Scalar cubic and}\\ \text{quartic self interactions}\\ \text{from } -V(\Phi).\end{array}\right)$$

$$\overset{\text{C}}{+A^{\mu b}\partial_\mu\phi_i\, gT^b_{ij}\phi_j} + \overset{\text{D}}{A^a_\mu A^{\mu b}[gT^a\langle\phi\rangle]_i\, gT^b_{ij}\phi_j} + \overset{\text{E}}{\frac{1}{2}A^a_\mu A^{\mu b}(gT^a\phi)_i(gT^b\phi)_i}$$

$$\overset{\text{F}}{+gf^{abc}(\partial^\mu\bar{\eta}^a)\eta^b A^c_\mu} - \overset{\text{G}}{\xi[gT^a\langle\phi\rangle]_i\bar{\eta}^a\eta^b(gT^b_{ij}\phi_j)}$$

If $V(\Phi)$ is a quartic polynomial in Φ, we have:

$$V(\Phi) = \frac{1}{2}\underbrace{\left.\frac{\partial^2 V}{\partial\Phi_i\partial\Phi_j}\right|_{\langle\phi\rangle}}_{M^2_{ij}}\phi_i\phi_j + \frac{1}{3!}\underbrace{\left.\frac{\partial^3 V}{\partial\Phi_i\partial\Phi_j\partial\Phi_k}\right|_{\langle\phi\rangle}}_{\equiv C_{ijk}}\phi_i\phi_j\phi_k + \frac{1}{4!}\underbrace{\left.\frac{\partial^4 V}{\partial\Phi_i\partial\Phi_j\partial\Phi_k\partial\Phi_l}\right|_{\langle\phi\rangle}}_{\equiv C_{ijkl}}\phi_i\phi_j\phi_k\phi_l$$

$$= \frac{1}{2}M^2_{ij}\phi_i\phi_j + \frac{1}{3!}C_{ijk}\phi_i\phi_j\phi_k + \frac{1}{4!}C_{ijkl}\phi_i\phi_j\phi_k\phi_l$$

Clean up – Define:

Goldstone boson decay matrix: $F^a{}_i = gT^a_{ij}\langle\phi\rangle_j$

the gauge boson mass matrix, $(m_A^2)^{ab} \equiv m_A^2(\langle\phi\rangle)^{ab} = [gT^a\langle\phi\rangle]_i[gT^b\langle\phi\rangle]_i = FF^T$

the pseudo-Goldstone mass matrix, $(m_A^2)_{ij} \equiv m_A^2(\langle\phi\rangle)_{ij} = \underbrace{[gT^a\langle\phi\rangle]_i[gT^a\langle\phi\rangle]_j}_{\substack{\text{Grammian matrix}\\ \text{(of the form } v^T v)}} = F^T F$

Then $[gT^a\langle\phi\rangle]_i\, gT^b_{ij} = \dfrac{1}{2}\dfrac{\partial(m_A^2)^{ab}}{\partial\langle\phi\rangle_j}$

$$(gT^a\phi)_i(gT^b\phi)_i = \frac{1}{2}\frac{\partial^2(m_A^2)^{ab}}{\partial\langle\phi\rangle_j\partial\langle\phi\rangle_k}\phi_j\phi_k$$

So, the final Lagrangian is $\mathcal{L} = \mathcal{L}^{\text{Quad}} + \mathcal{L}^{\text{Int}}$:

$$\mathcal{L}^{\text{Quad}} = \frac{1}{2}\phi_i\left(-\partial^2\delta_{ij} - M^2_{ij} - \xi\,(m_A^2)_{ij}\right)\phi_j$$

$$+ \frac{1}{2}A^a_\mu\left(\partial^2 g^{\mu\nu}\delta^{ab} - \left(1-\frac{1}{\xi}\right)\partial^\mu\partial^\nu\delta^{ab} + (m_A^2)^{ab}g^{\mu\nu}\right)A^b_\nu$$

$$+ \bar{\eta}^a\left(-\partial^2\delta^{ab} - \xi\,(m_A^2)^{ab}\right)\eta^b$$

$$\mathcal{L}^{\text{int}} = +g f^{abc}\,\partial_\mu A^a_\nu A^{\mu b}A^{\nu c} - \frac{g^2}{4}f^{abc}f^{ace}A^b_\mu A^c_\nu A^{\mu d}A^{\nu e} - \frac{1}{3!}c_{ijk}\,\phi_i\phi_j\phi_k$$

$$-\frac{1}{4!}c_{ijkl}\,\phi_i\phi_j\phi_k\phi_l + A^{\mu a}\partial_\mu\phi_i\,gT^a_{ij}\phi_j + \frac{1}{2}\frac{\partial(m_A^2)^{ab}}{\partial\langle\phi\rangle_i}A^a_\mu A^{\mu b}\phi_i$$

$$+\frac{1}{2}\frac{\partial^2(m_A^2)^{ab}}{\partial\langle\phi\rangle_i\partial\langle\phi\rangle_j}A^a_\mu A^{\mu b}\phi_i\phi_j + g f^{abc}(\partial^\mu\bar{\eta}^a)\eta^b A^c_\mu - \frac{\xi}{2}\frac{\partial(m_A^2)^{ab}}{\partial\langle\phi\rangle_i}\bar{\eta}^a\eta^b\phi_i$$

This last term serves to remove the 0's belonging to each of the M_{ij}, $(m_A)_{ij}$ subspaces. Together, they form $1/p^2$ matrix proportional to the identity.

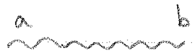
Feynman Rules $\left(\text{for } G_{Amp}(-p,\dots p)\right)$

Propagators

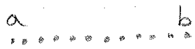
Scalar Fields 

$$= \frac{i}{p^2 - M_{ij}^2} + \frac{i}{p^2 - \xi (m_A^2)_{ij}} - \frac{\delta_{ij}}{p^2}$$

(form only valid at tree-level minimum)

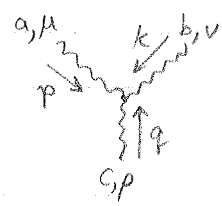
Gauge Fields 

$$= \frac{-i}{p^2 - (m_A^2)^{ab} + i\epsilon}\left(g^{\mu\nu} - (1-\xi)\frac{p^\mu p^\nu}{p^2 - \xi (m_A^2)^{ab} + i\epsilon}\right)$$

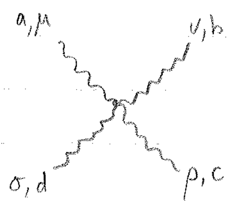
Ghost Fields 

$$= \frac{i}{p^2 - \xi (m_A^2)^{ab} + i\epsilon}$$

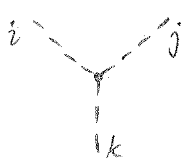
Vertices



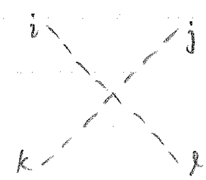
$$= g f^{abc}\left(g_{\mu\nu}(k-p)_\rho + g_{\nu\rho}(q-k)_\mu + g_{\rho\mu}(p-q)_\nu\right)$$



$$= -ig^2\Big[f^{abe}f^{ecd}\left(g^{\mu\rho}g^{\nu\sigma} - g^{\mu\sigma}g^{\nu\rho}\right) + f^{ace}f^{ebd}\left(g^{\mu\nu}g^{\rho\sigma} - g^{\mu\sigma}g^{\nu\rho}\right) + f^{ade}f^{ebc}\left(g^{\mu\nu}g^{\rho\sigma} - g^{\mu\rho}g^{\nu\sigma}\right)\Big]$$

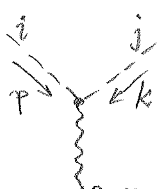


$$= -i\, c_{ijk}$$

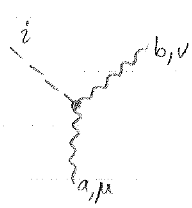


$$= -i\, c_{ijkl}$$

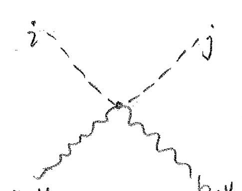
Using complex scalar fields, there is an i in this Feynman rule



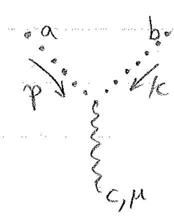
$$= g\, T^a_{ij}(p-k)$$



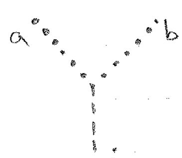
$$= i\,\frac{\partial (m_A^2)^{ab}}{\partial\langle\phi\rangle_i}\, g^{\mu\nu}$$



$$= 2i\,\frac{\partial^2 (m_A^2)^{ab}}{\partial\langle\phi\rangle_i\,\partial\langle\phi\rangle_j}\, g^{\mu\nu}$$



$$= -\frac{1}{2}\, g f^{abc}(p-k)_\mu$$



$$= \frac{-i\xi}{2}\,\frac{\partial (m_A^2)^{ab}}{\partial\langle\phi\rangle_i}$$

Multiply by (-1) for each Ghost loop