Why a force carrier becomes a gauge field

Scope

We use the $U(1)$ case as the clean example, then how massive gauge bosons arise without abandoning the gauge principle.

For familiar gauge forces, the mediator is represented by a vector field,

$$A_\mu.$$

A vector field carries spin one, so its quanta are bosons

$$A_\mu \quad \Longrightarrow \quad s = 1 \quad \Longrightarrow \quad \text{boson.}$$

But spin one alone is not enough.

Massless spin–1

$$\lambda = +1, -1.$$

Massive spin–1

$$\lambda = +1, 0, -1.$$

Gauge theory tells us which components are physical, and how a longitudinal mode can appear consistently.

1. Matter symmetry forces the gauge field

Start with a matter field. The free Dirac Lagrangian is invariant under a global phase rotation

$$\mathcal{L}_{\text{matter}} = \bar{\psi}\,(i\gamma^\mu\partial_\mu - m)\,\psi, \qquad \psi(x) \to e^{iq\alpha}\psi(x).$$

By Noether's theorem,

$$\text{global } U(1) \text{ symmetry} \quad \Longrightarrow \quad \partial_\mu j^\mu = 0, \qquad j^\mu = \bar{\psi}\gamma^\mu\psi.$$

The obstruction

If the phase becomes local,

$$\alpha \to \alpha(x),$$

then

$$\partial_\mu\psi \to e^{iq\alpha(x)}\left[\partial_\mu\psi + iq(\partial_\mu\alpha)\psi\right].$$

Therefore $\partial_\mu\psi$ no longer transforms like ψ.

The moment symmetry becomes local, the theory asks for a new field.

2. The compensating field becomes the mediator

Introduce a vector field and replace the ordinary derivative by a covariant derivative

$$D_\mu = \partial_\mu + iqA_\mu.$$

Require

$$A_\mu \to A_\mu - \partial_\mu \alpha,$$

so that

$$D_\mu \psi \to e^{iq\alpha(x)} D_\mu \psi.$$

Therefore local invariance is restored.

The key turn

The field introduced to protect local symmetry automatically produces the interaction

$$\mathcal{L}_{\text{int}} = -qj^\mu A_\mu.$$

matter symmetry $\to$ current $\to$ local rule $\to$ gauge field $\to$ force carrier

The compensating field is no longer an auxiliary trick; it is the mediator.

3. Dynamics, mass problem, and mass generation

The mediator needs dynamics, but the dynamics must respect the same gauge rule

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu, \qquad \mathcal{L}_{\text{gauge}} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}.$$

A direct mass term, $\mathcal{L}_{\text{mass}} = \frac{1}{2} m^2 A_\mu A^\mu$, is **not gauge invariant**.

Higgs mechanism

Introduce a charged scalar field with a nonzero vacuum value

$$\mathcal{L}_\phi = |D_\mu \phi|^2 - V(\phi), \qquad \langle \phi \rangle = \frac{v}{\sqrt{2}}.$$

Then its covariant kinetic term contains $|D_\mu \phi|^2 \supset \frac{1}{2} q^2 v^2 A_\mu A^\mu$. Thus,

$$\boxed{m_A = qv}$$

Mass comes from the vacuum structure, not from inserting a forbidden term by hand.

4. What becomes physical?

The gauge principle is not simply thrown away. Instead, the physical spectrum is reorganized

$$\underbrace{\text{massless } A_\mu}_{\text{2 modes}} + \underbrace{\text{Goldstone mode}}_{\text{1 mode}} \longrightarrow \underbrace{\text{massive } A_\mu}_{\text{3 modes}}.$$

What is that?

The would-be Goldstone boson supplies the longitudinal polarization of the massive vector boson. This is why the weak bosons can be massive gauge bosons $W^{\pm}$, Z^{0} are massive, but their masses arise through symmetry breaking.

If gauge symmetry is partly redundancy,

how can a redundancy help determine the mass of a real particle?

Is mass intrinsic to the force carrier,
or does it also belong to the vacuum it lives in?