Quantum Chromo-Dynamics (QCD) [Theory of Strong (Nuclear) Force]: a brief/rough history (based on section 17.1 of Peskin, Schroeder)

- Begin with Yukawa's theory (1949 Nobel prize): strong (nuclear) force between protons, neutrons (spin-1/2) due to their coupling to / exchange of pions (spin-0), as discussed briefly in pion (π) - nucleon (N) system in the context of (global) SU(2) symmetry
- Later on, a plethora of other hadrons (strongly interacting particles) were discovered, classified as mesons (spin-0, 1...) and baryons/anti-baryons (spin-1/2, 3/2 ...)
- In order to have a simpler underlying model for this hadron "zoo", Gell-Mann, Ne'eman, Zweig (in 1960's) proposed that hadrons have sub-structure, i.e., are all made of: up (u), down (d) and strange (s) quarks (much smaller number of constituents), with fractional electric charges of $+2/3$, $-1/3$ & $-1/3$, respectively: there is an approximate SU(3) global symmetry (rotating u, d, s into each other), which can be used to classify the bound state hadrons; also it matches SU(2) of π-N system [i.e., restricting to hadrons made of u, d (lighter quarks) only (s is heavier, but still lighter than typical binding energy of ~ GeV, which accounts for large fraction of hadron masses].

- The quark theory predicted new hadrons/ bound states (and some of their properties), which were observed subsequently
- While quark theory was successful as above, it lacked answers to questions such as what force binds quarks into hadrons in such a way that isolated / fractionally charged quarks are not seen?
- More empirically, there is a problem related to spin-3/2, doubly charged particle/called $\boxed{\Delta^{++}}$. It can be interpreted as (uuu) bound state/baryon, with zero orbital angular and spins of all 3 u's being parallel : however, such a totally symmetric combination (of fermions) violates spin-statistics theorem
- So, Gell-Mann, Greenberg (@ UMD!) also in 1960's proposed that quarks carry (in addition to spin and flavor) an internal quantum number ("color") : each quark is triplet (3) of - global at this stage - $\boxed{SU(3)_{\text{color}}}$ symmetry [eventually, this became QCD : see below].
- It is also assumed that all hadrons are color singlet : 2 options are (as discussed in group theory - detour in context of Yukawa couplings of SM fermions) $\boxed{\bar{q}_\alpha q'_\alpha}$ ($\alpha = 1,2,3$ is color), giving mesons and $\boxed{q_\alpha q'_\beta q''_\gamma \epsilon^{\alpha\beta\gamma}}$, giving baryons (and their anti-particles, made of $\bar{q}$'s, i.e., anti quarks).

- So, Δ^{++} is symmetric in spin & flavor space, but antisymmetric in color, thus being consistent with spin-statistics theorem
- The "colored" (global) quark model raised its own questions: what is the physical role of color? Why should observed states/hadrons be color singlet (that seems like an ad-hoc assumption, even if it explains Δ^{++} state)?
- Han, Nambu (still in 1960's) then proposed to make SU(3) color symmetry local, i.e., a non-abelian gauge theory [note that Yang, Mills in 1950's had introduced such a theory as a more mathematical/theoretical possibility, i.e., not for explaining specific forces in Nature], thus giving a more physical role to color
- I guess idea was that SU(3) color gauge boson ("gluon") exchange binds quarks into hadrons [again, prototype here being the highly successful U(1) gauge theory of QED, which binds proton & electron into hydrogen or electron-positron into positronium]
- However, perhaps gauged/colored quark model is still not convincing: how do we "make sense of" (e.g., calculate in) a strongly coupled gauge theory (cf. use of perturbation theory for weakly coupled QED) (?!) Hadrons being color singlets is still a puzzle [after all, isolated electrically charged particles such as electron are observed, so why not colored/SU(3) charged

quarks (maybe answer lies in strong coupling) [?!]

— Almost independently of above more theoretical developments, came (also in 1960's) deep inelastic scattering (DIS) - type of experiments, e.g. electron - nucleon collisions with energy transfer $\boxed{\gtrsim \text{GeV}}$ (mass/binding energy of nucleon).

— DIS showed that protons/neutrons are made of constituents (dubbed "partons"), which are weakly coupled at energies $\boxed{\gg \text{GeV}}$ (but presumably strongly coupled / bound into protons/neutrons at lower energies).

— It was natural to identify (empirical) partons with quarks : so it boils down to searching for interactions (gauge / Yukawa ... couplings) of quarks which are asymptotically free [AF], i.e., become stronger (weaker) in IR (UV)

— Of course, it was [known] that gauge coupling, e.g., in QED (or presumably Yukawa couplings) "run", but [initial] candidates were IR free instead, as we saw in case of QED ...

... it all [came together] with the discovery (in 1970's)

— by Gross, Wilczek; Politzer; 't Hooft (Nobel prize for first 3 in 2004) - that (in general) non-abelian gauge theories can be [AF] if running is dominated by contributions of gauge boson loops/ self-interactions.

- So, above $\boxed{\text{SU(3) color}}$ - gauged (QCD) - could do the job: well, we'd better address the issues mentioned earlier with the gauged/colored quark model (of Han, Nambu)!
- Indeed, the answers lie in the $\boxed{2}$ regimes of $\boxed{\text{QCD}}$ following from $\boxed{\text{AF}}$, i.e., at $\boxed{\text{energies} \gg \text{GeV}}$, we can indeed calculate (analytically) using perturbation theory (since QCD coupling constant is weak in this limit)
- whereas, in the opposite case of $\boxed{\text{energies} \lesssim \text{GeV}}$, i.e., strong QCD coupling constant (non-perturbatively) binding quarks into hadrons, we can use $\boxed{\text{lattice}}$ gauge theory, i.e, discretize space-time. In this way (i.e., numerically), Wilson showed "color is confined", i.e., observed / finite-energy asymptotic states are color singlets, so earlier assumption is a consequence of non-abelian gauge theory
- Here's a rough/intuitive picture of color confinement, i.e., why isolated quarks are not seen. Suppose we $\boxed{\text{try}}$ to separate a color singlet state, e.g., a $\boxed{q\bar{q}'}$ meson. In this process (see figure)

a "tube" of gauge field forms between q & $\bar{q}$, with fixed energy density/radius, in turn, due to strong coupling (cf. EM). Thus, energy "cost" of separation $\propto$ distance between q & $\bar{q}$. Eventually, it is energetically favorable for flux tube to "break", i.e, form two mesons instead of isolating the original quark and anti-quark

- Henceforth, we focus on short-distance/high-energy (>> GeV) limit of QCD, where (again) we can use Feynman diagrams/perturbation theory to make predictions, i.e., we will calculate (underlying) processes with weakly-coupled quarks & gluons

- However, in the end, we have to "connect" these weakly-coupled partons to states which are actually observed (initially and/or finally), i.e., hadrons

- So, it seems there's "no escape" from other (strongly-coupled, long distance) regime! Nonetheless, we will show how this strong coupling can be "by-passed" (therein lies subtlety/non-triviality of this program), allowing us to calculate (some) observables involving hadrons.