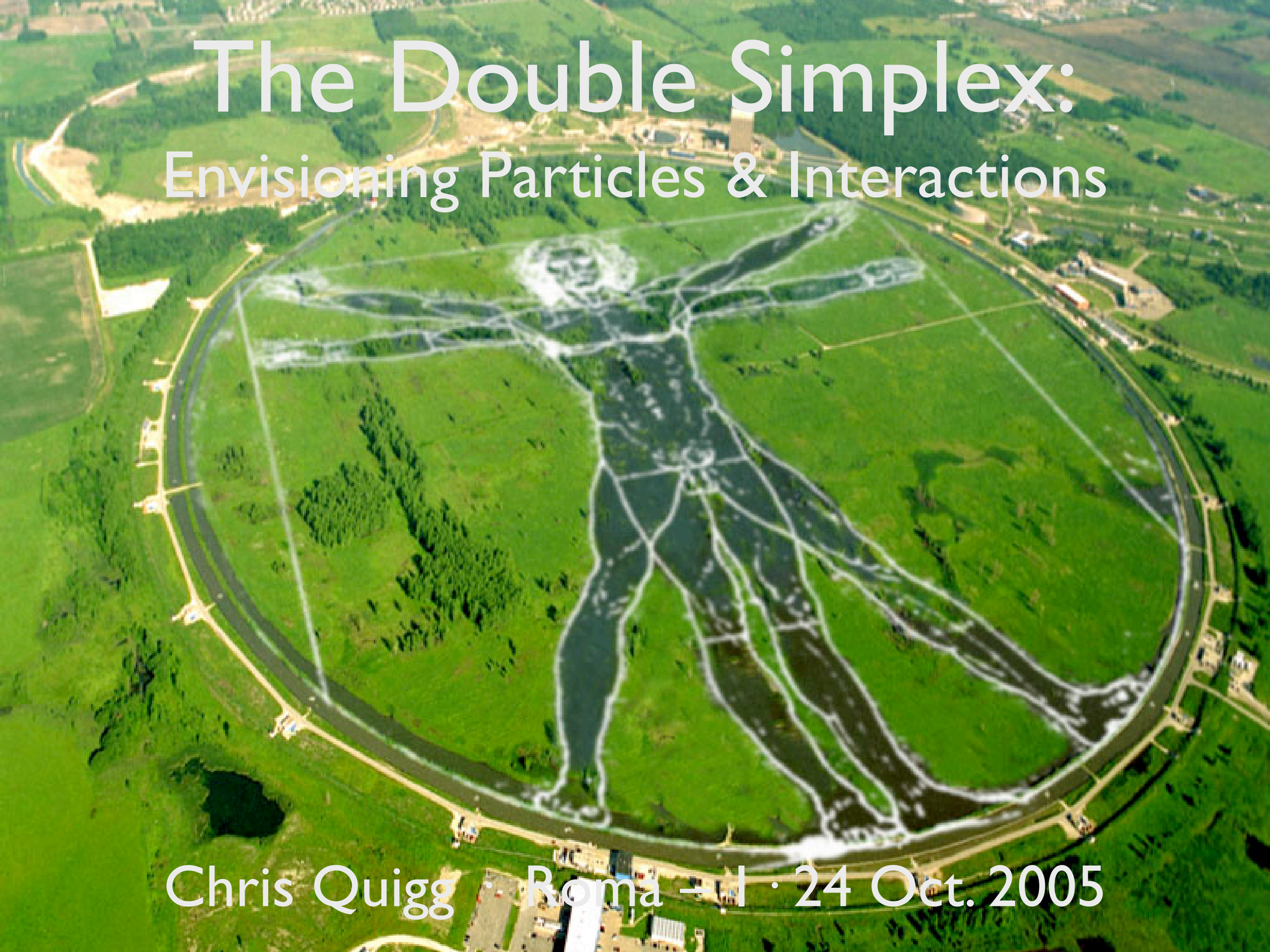
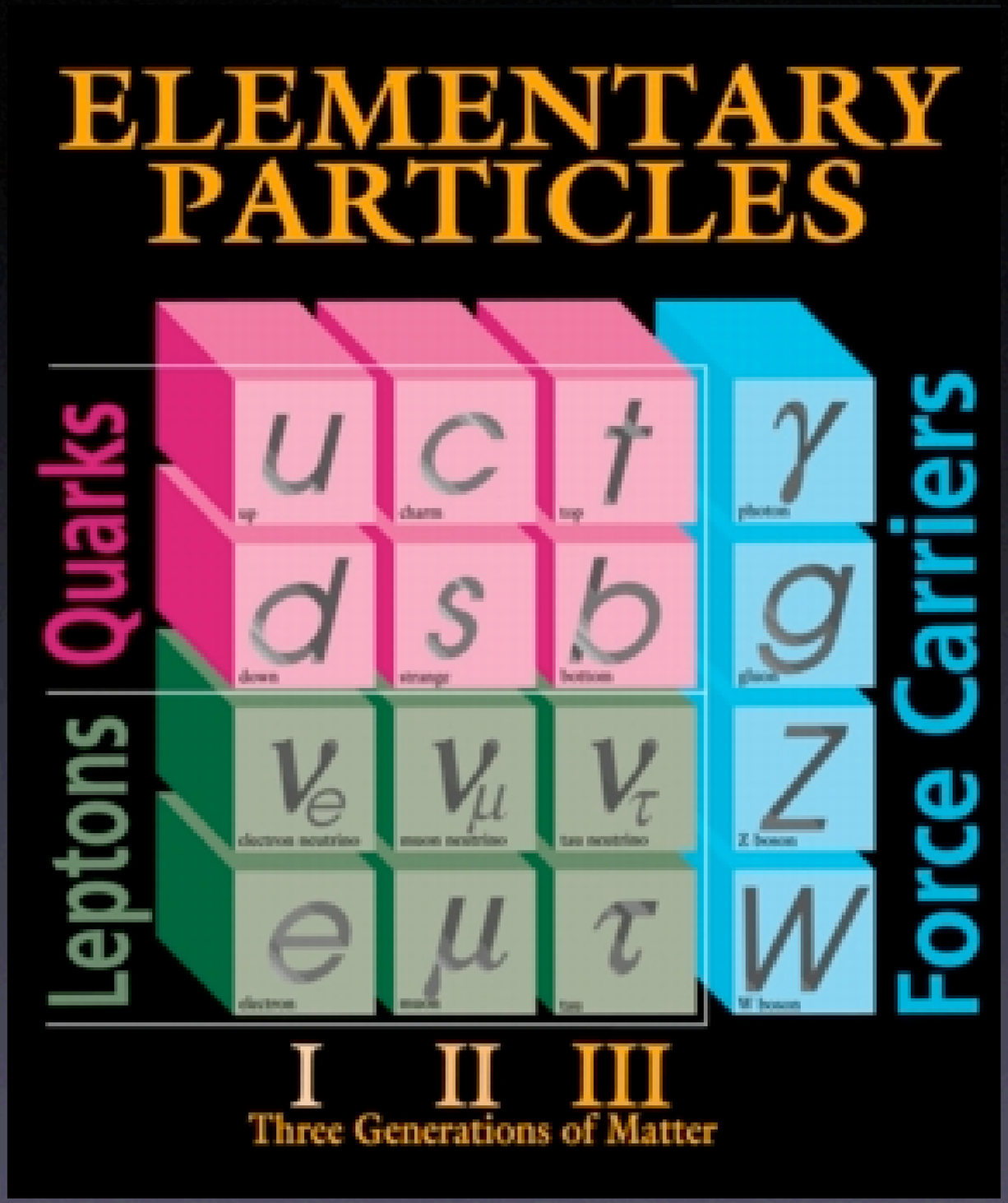
The Double Simplex:

Envisioning Particles & Interactions



Chris Quigg · Roma 1 · 24 Oct. 2005

ELEMENTARY PARTICLES



Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

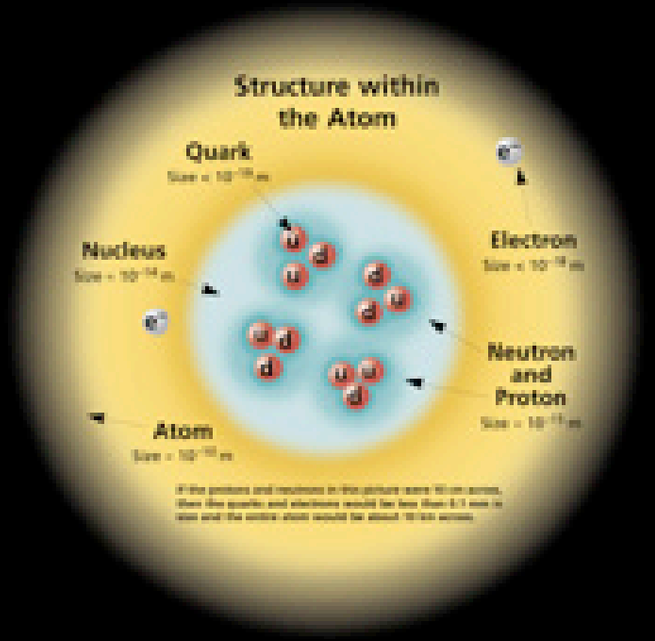
Leptons spin = 1/2			
Flavor		Mass GeV/c^2	Electric charge
ν_e	electron neutrino	$<1\times10^{-8}$	0
e	electron	0.000511	−1
ν_μ	muon neutrino	<0.0002	0
μ	muon	0.106	−1
ν_τ	tau neutrino	<0.02	0
τ	tau	1.7771	−1

Quarks spin = 1/2			
Flavor		Approx. Mass GeV/c^2	Electric charge
u	up	0.003	2/3
d	down	0.006	−1/3
c	charm	1.3	2/3
s	strange	0.1	−1/3
t	top	175	2/3
b	bottom	4.3	−1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of h, which is the quantum unit of angular momentum, where $h = 6.58\times10^{-22}$ GeV s = 1.05×10^{-34} J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton = 0.938 GeV/c^2 = 1.67×10^{-27} kg.



BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1			
Name		Mass GeV/c^2	Electric charge
γ	photon	0	0
W^-		80.4	−1
W^+		80.4	+1
Z^0		91.187	0

Strong (color) spin = 1			
Name		Mass GeV/c^2	Electric charge
g	gluon	0	0

Color Charge
Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, so strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and W and Z bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons
One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** ($q\bar{q}$) and **baryons** (qqq).

Residual Strong Interaction
The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

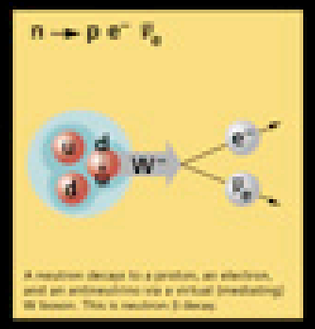
Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass - Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

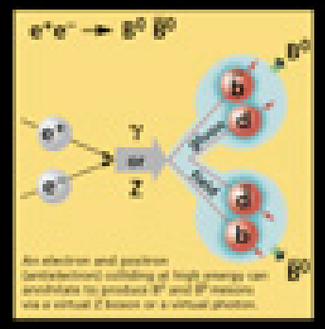
Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$					
Baryons are fermionic hadrons. There are about 120 types of baryons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	−1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	−1	1.672	3/2

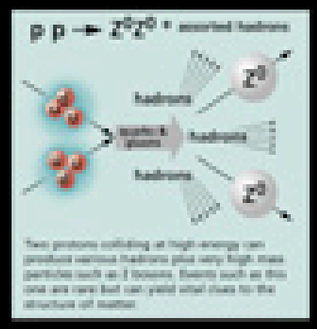
Mesons $q\bar{q}$					
Mesons are bosonic hadrons. There are about 140 types of mesons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	−1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2.980	0

Matter and Antimatter
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or − charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures
These diagrams are an artist's conception of physical processes. They are not exact and have no meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.







The Particle Adventure
Visit the award-winning web feature *The Particle Adventure* at
http://pdg.lbl.gov/cpep/adventure.html

Sponsors
This chart has been made possible by the generous support of
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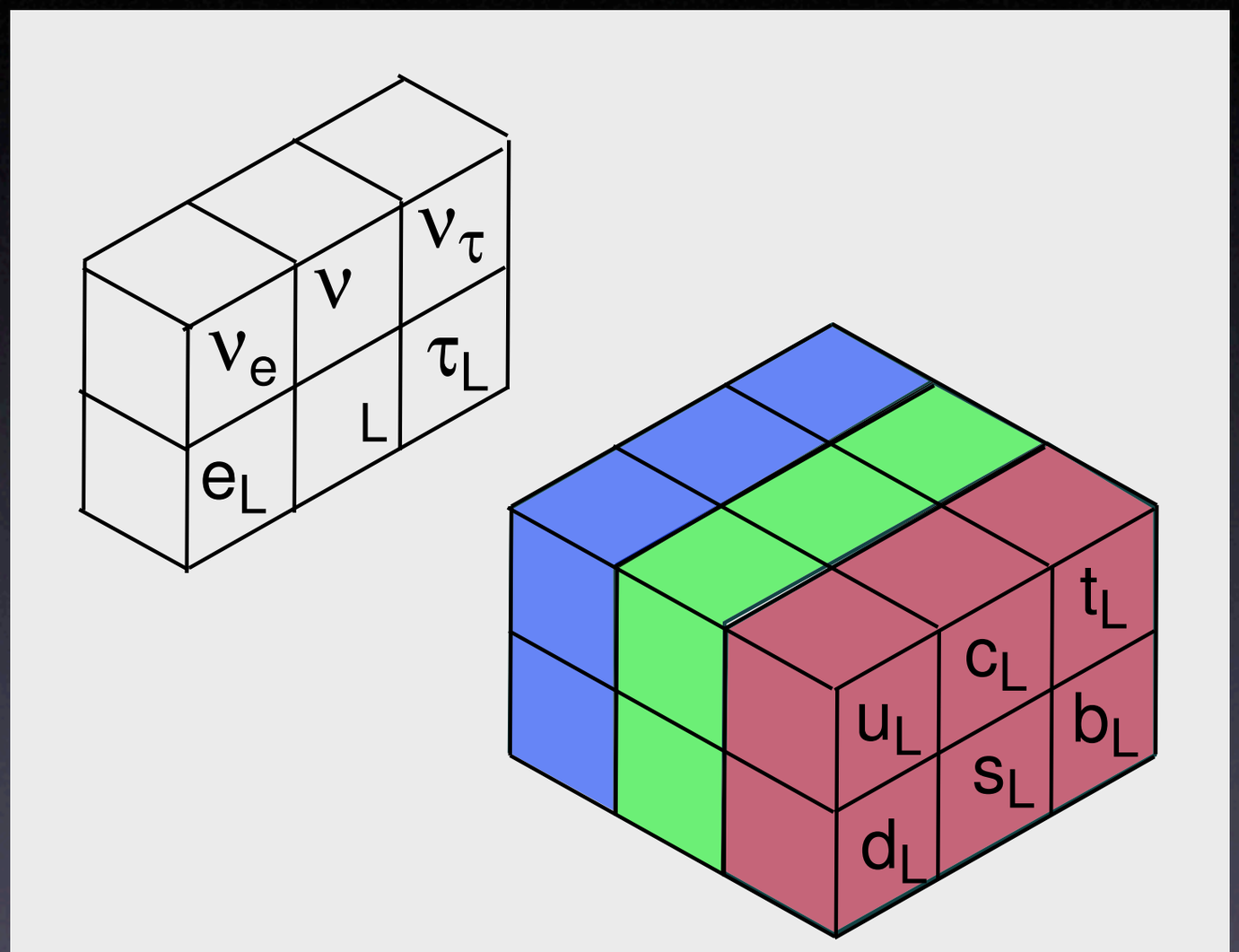
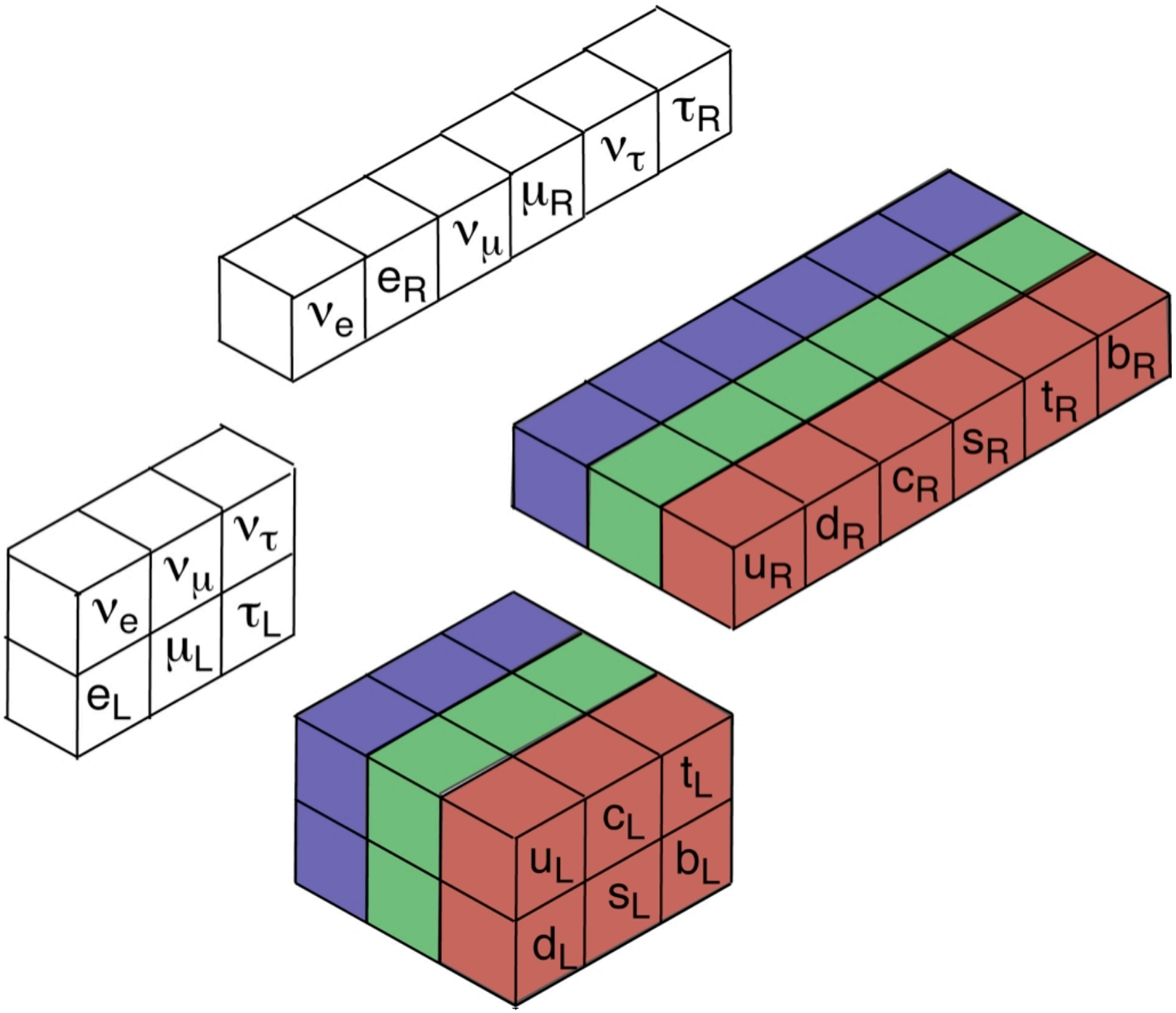

ν_τ
ν
ν_e
τ_L
L
e_L
t_L
c_L
u_L
b_L
s_L
d_L


ν_e
e_R
ν_μ
μ_R
ν_τ
τ_R
u_R
d_R
c_R
s_R
t_R
b_R
ν_e
ν_μ
ν_τ
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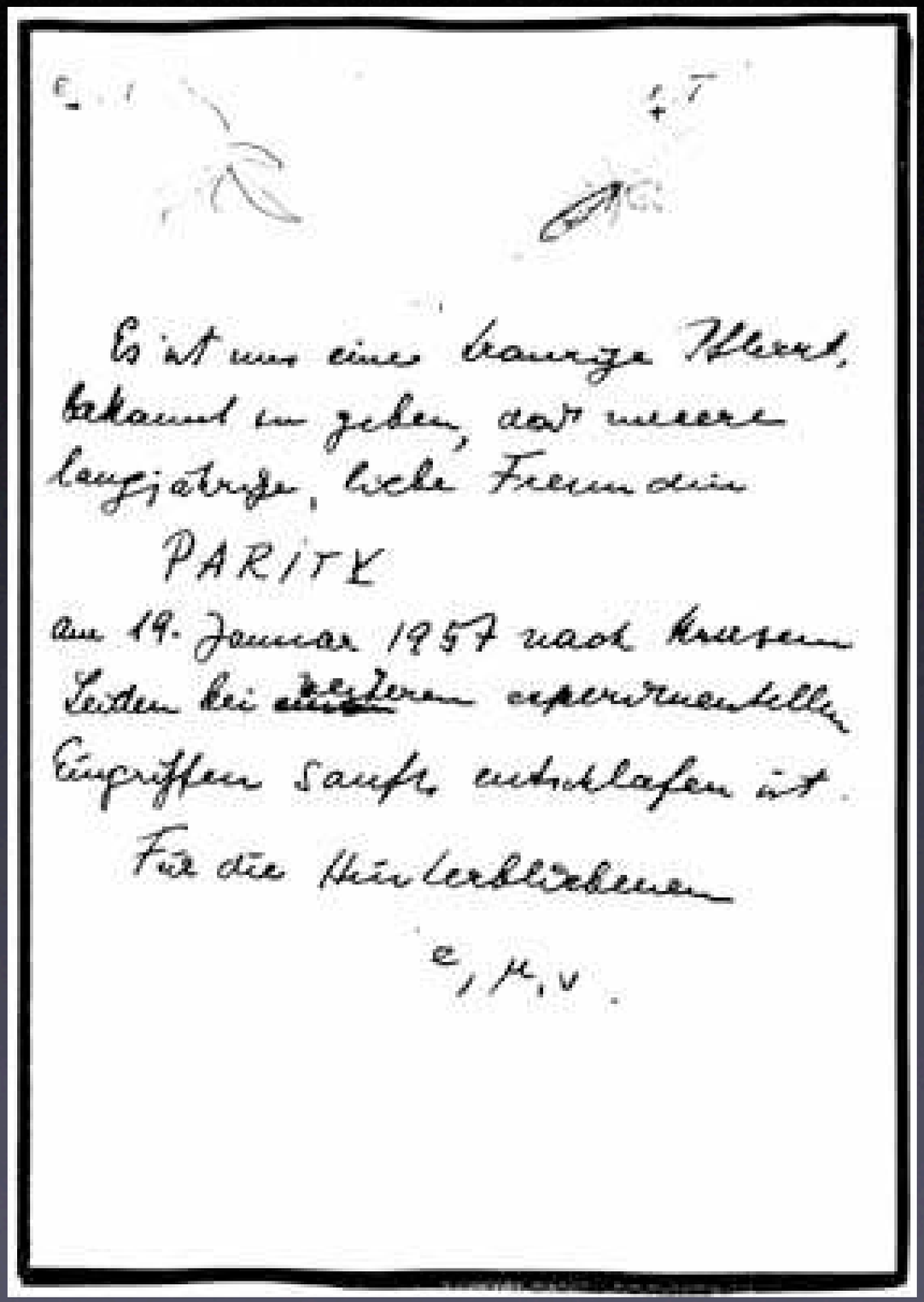
Wolfgang Pauli on the Downfall of Parity:



Es ist nun eine traurige Klarheit,
bekannt zu geben, daß unsere
langjährige, liebe Freundin

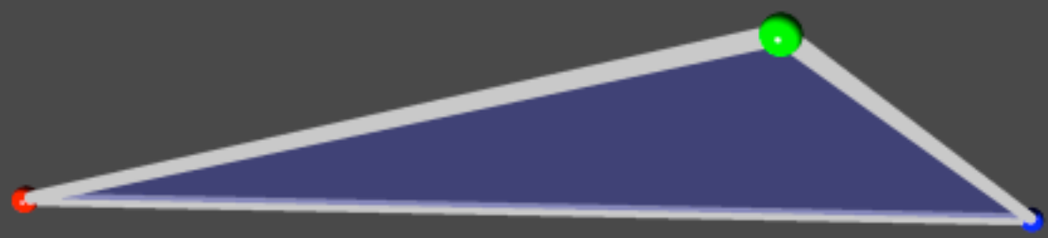
PARITY

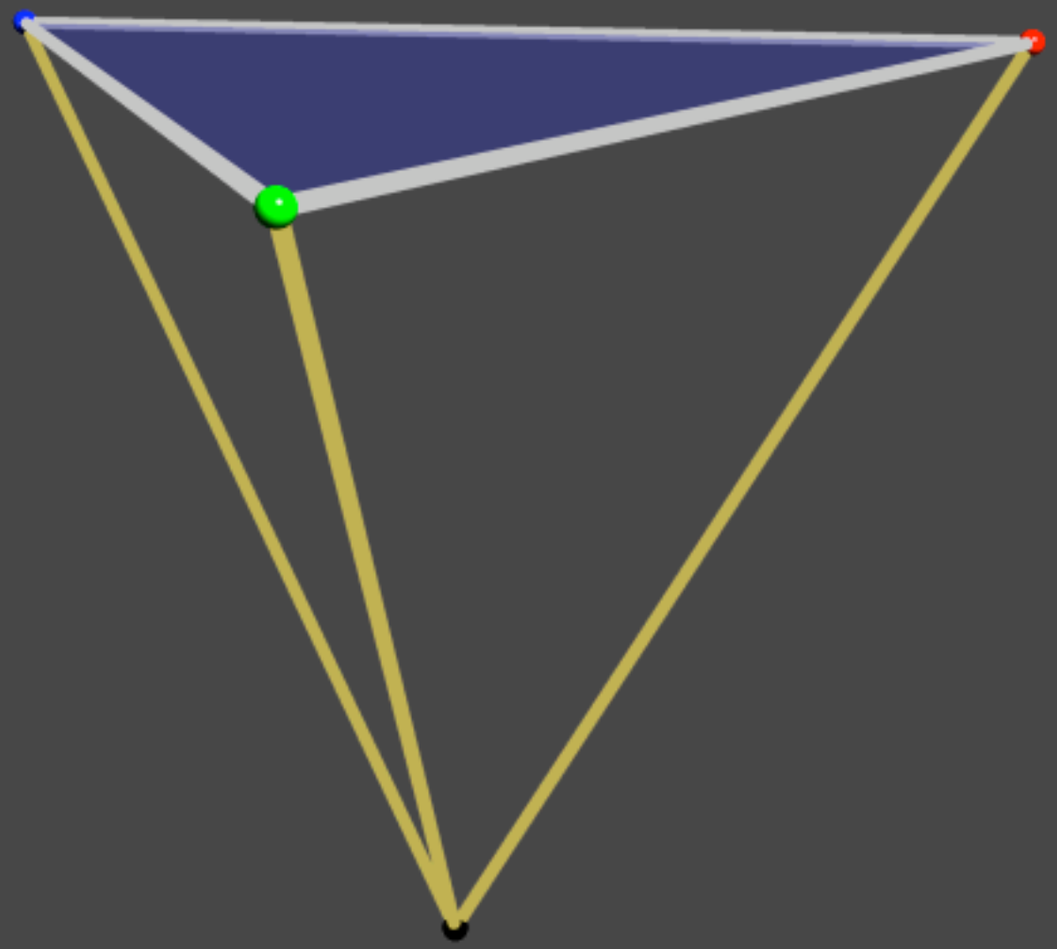
am 19. Januar 1957 nach kurzem
Leiden bei wohlbestellten experimentellen
Empfindungen sanft entschlafen ist.

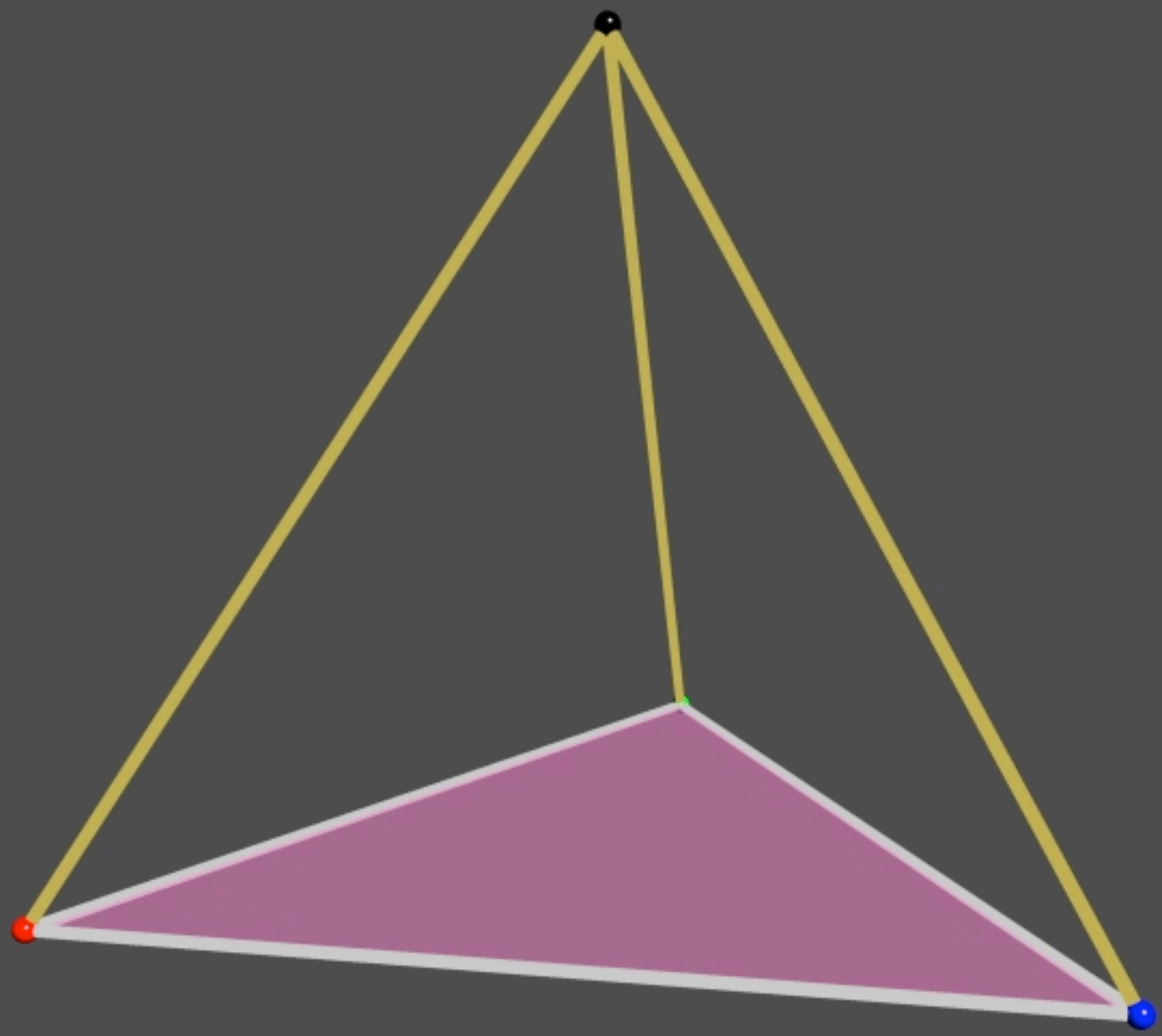
Für die Hinterbliebenen

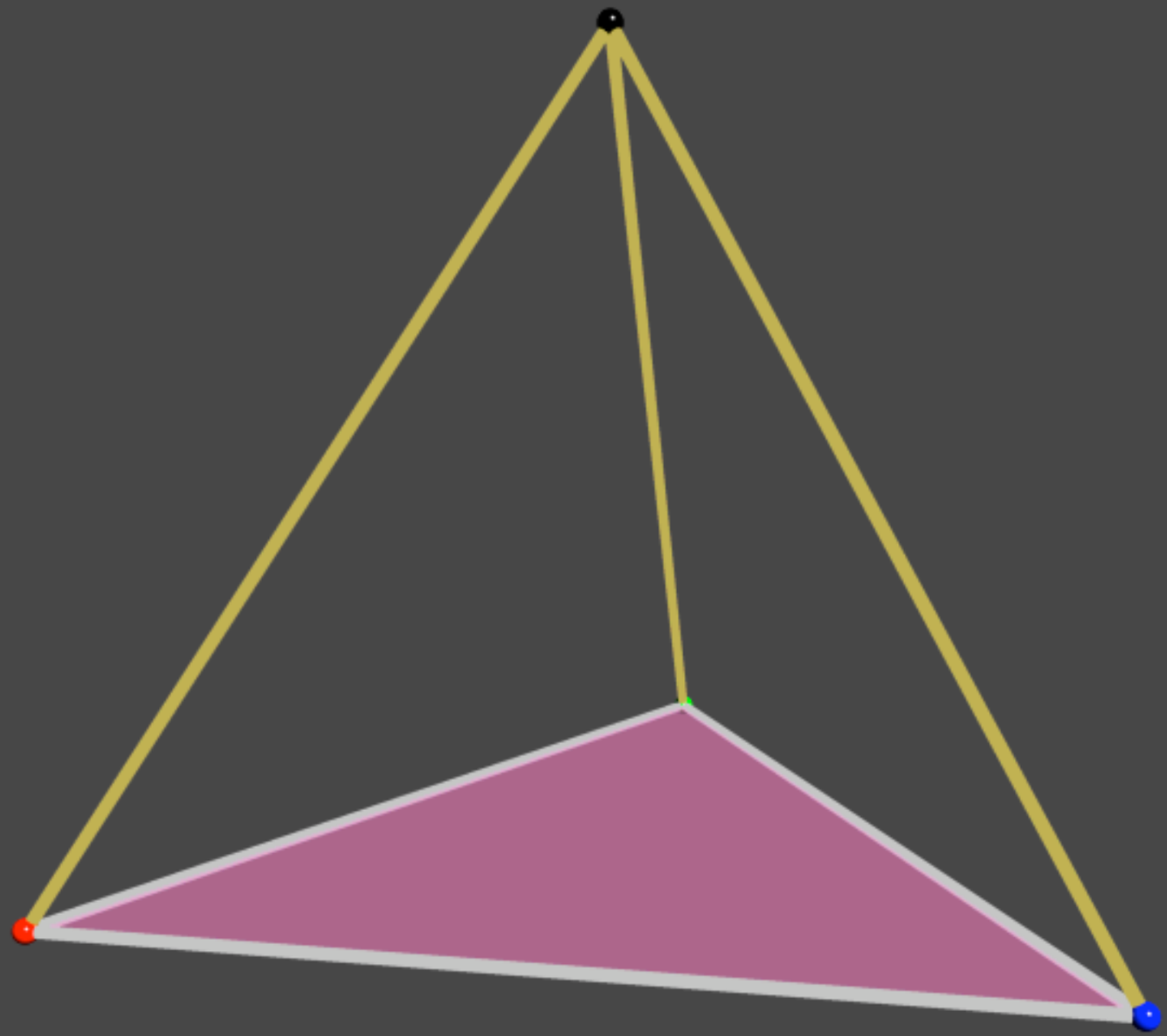
e, μ, ν.

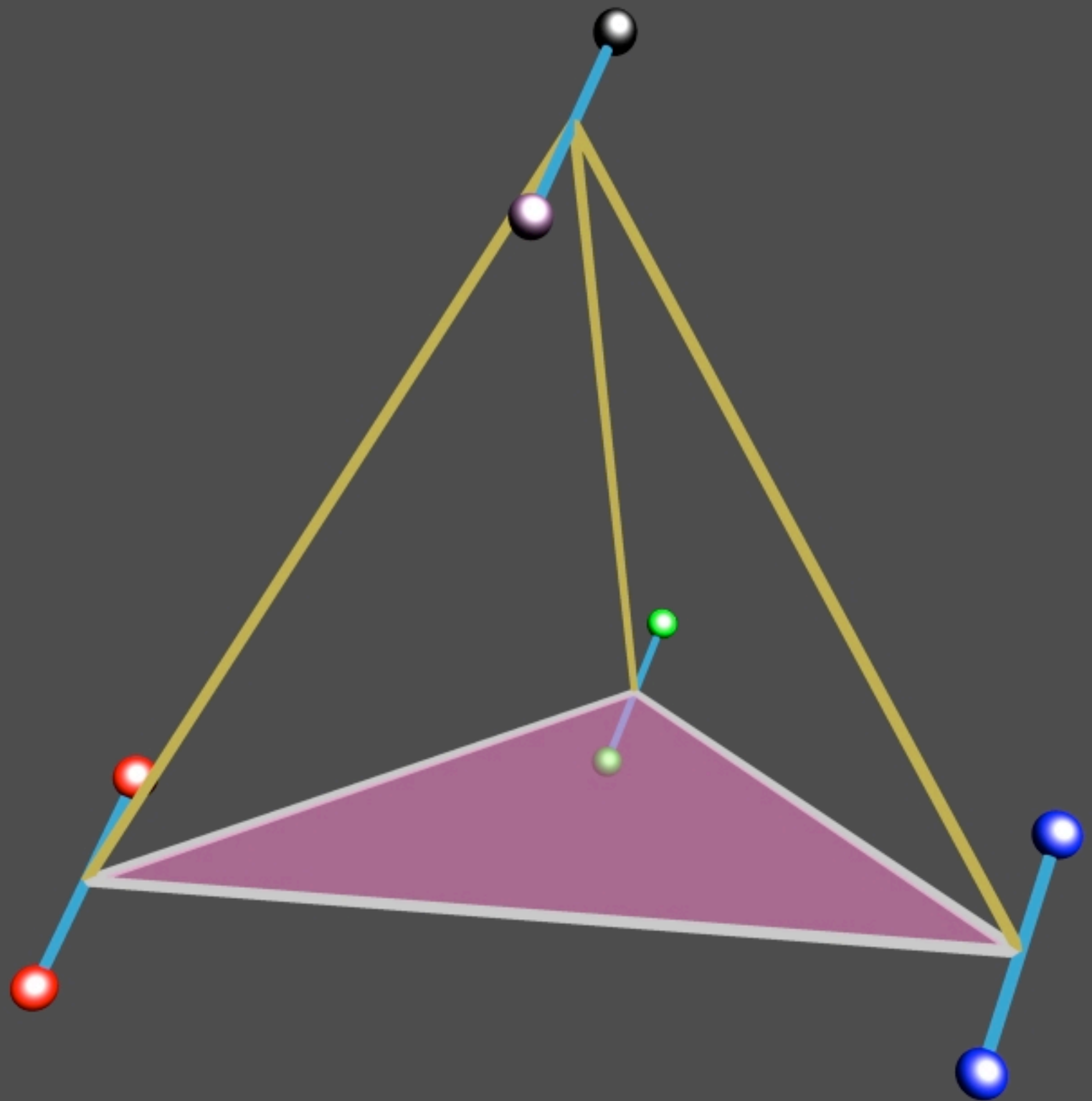
Pauli's Assertiveness Training

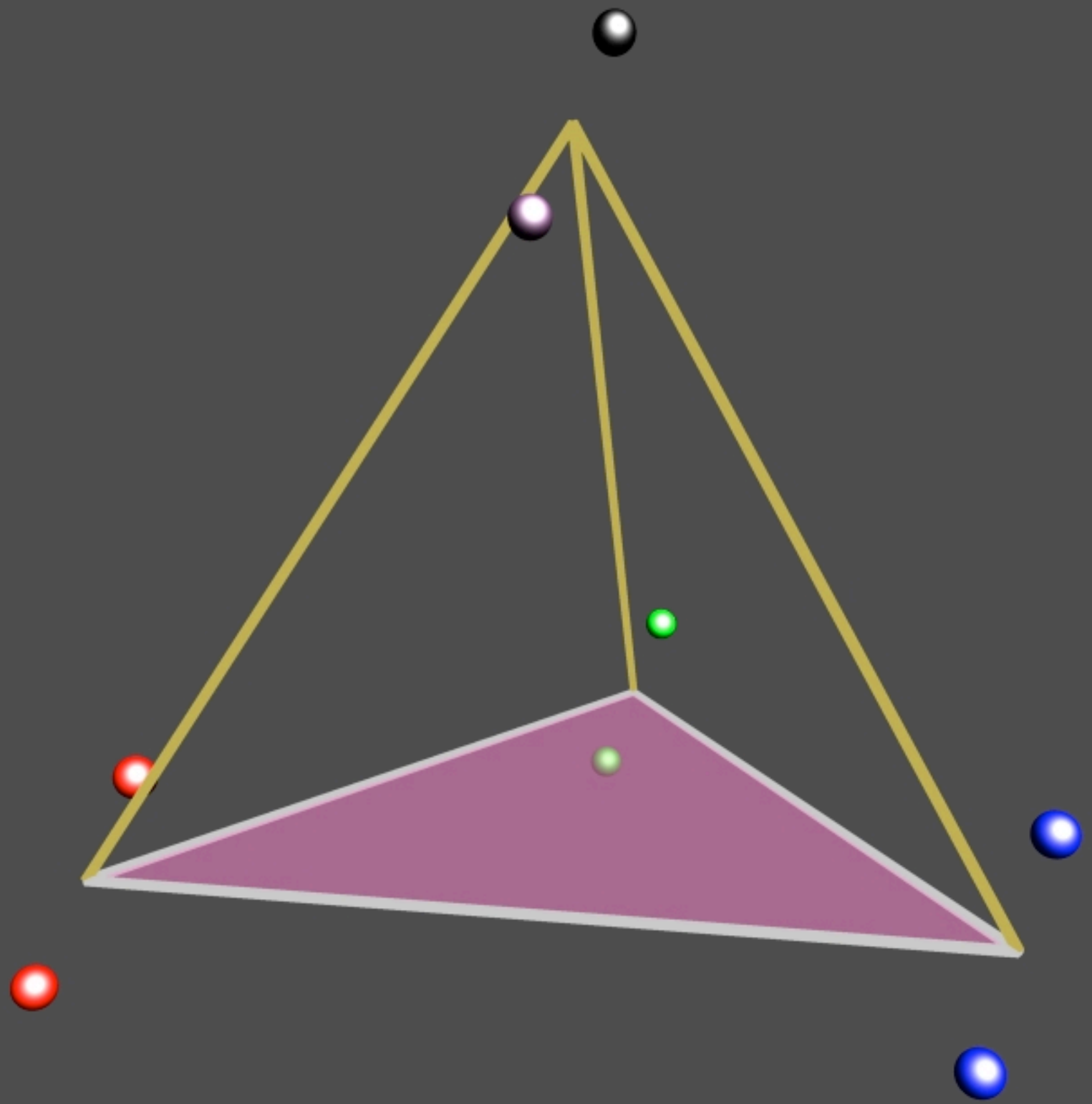


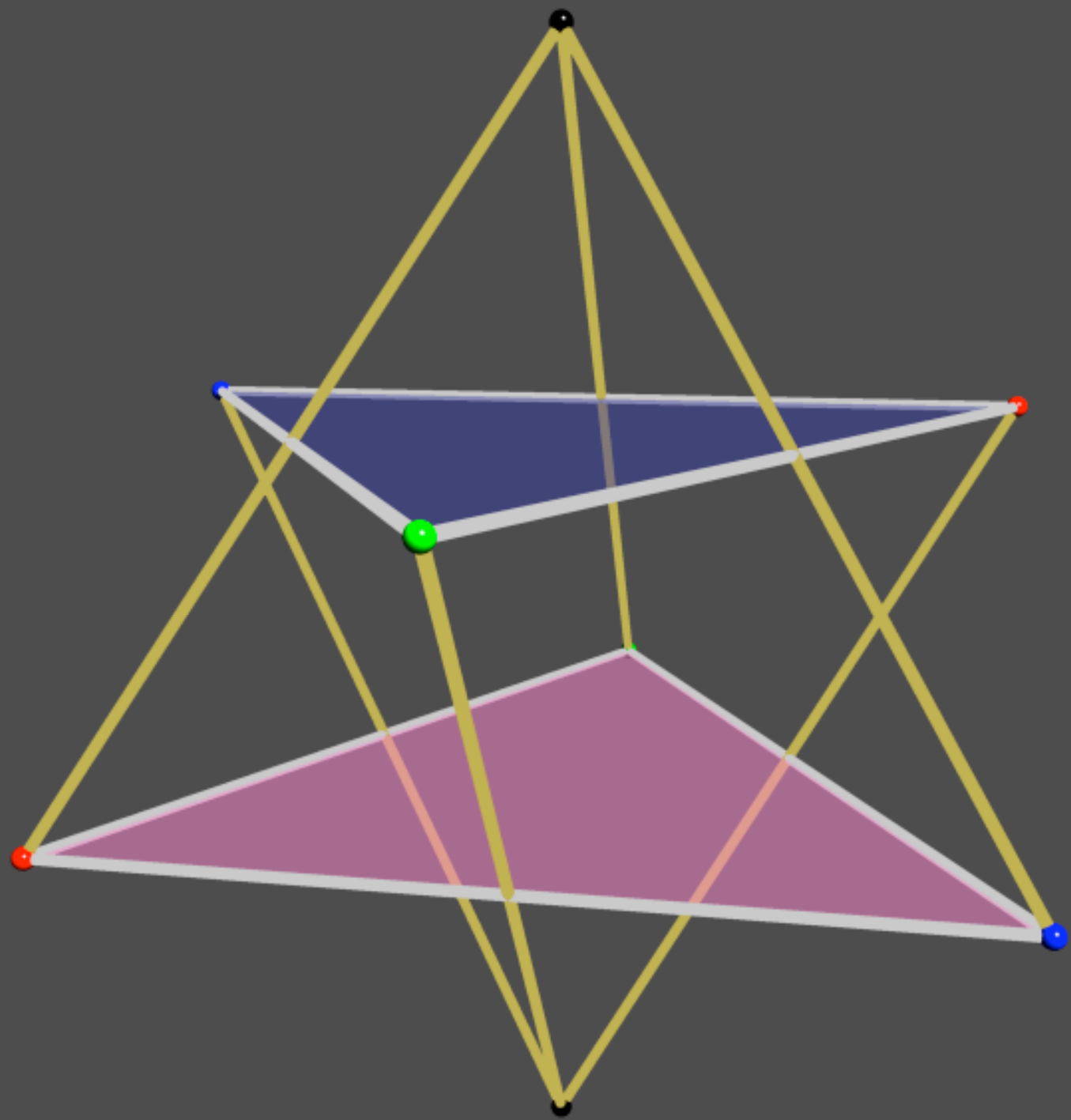


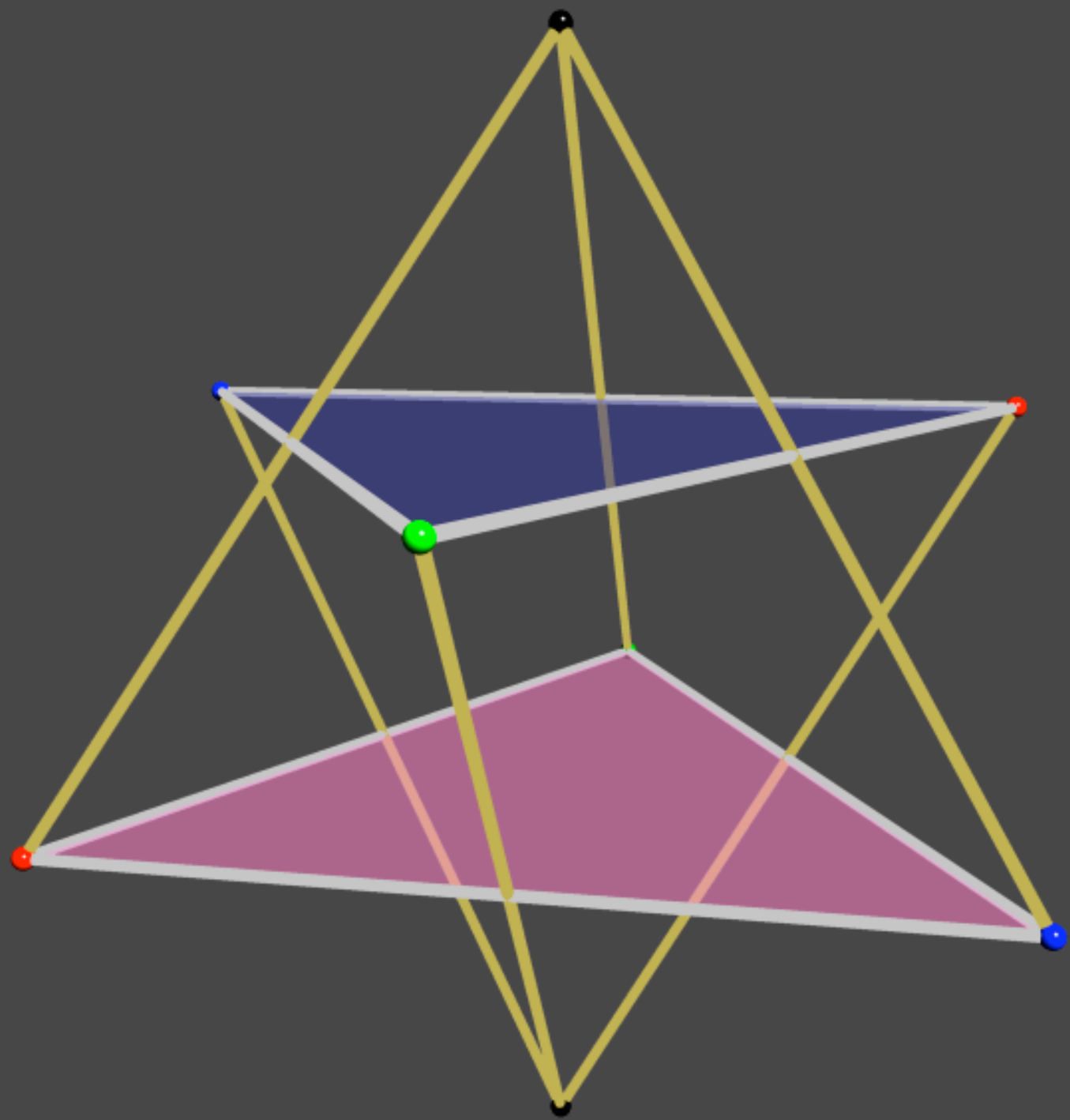


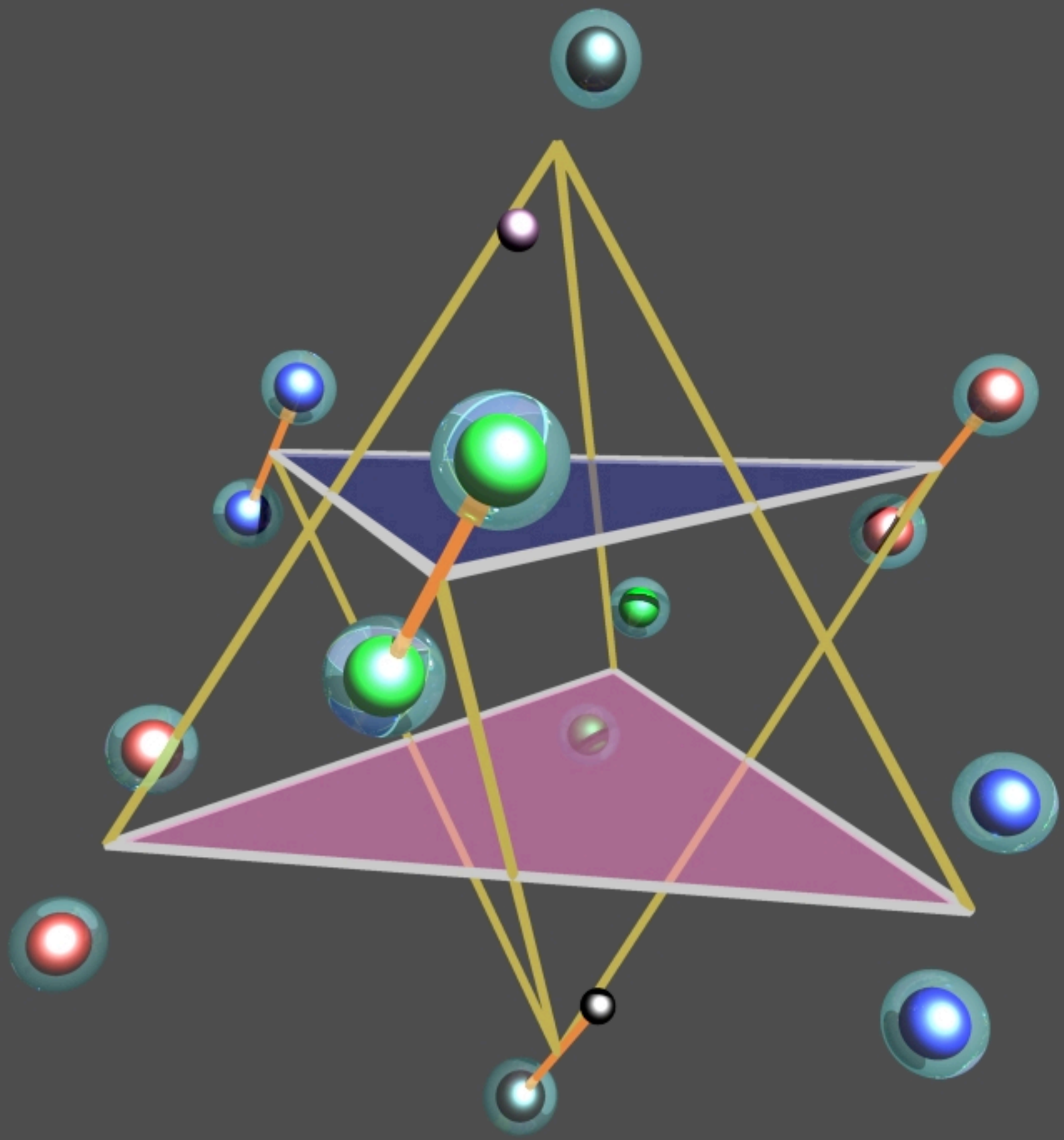


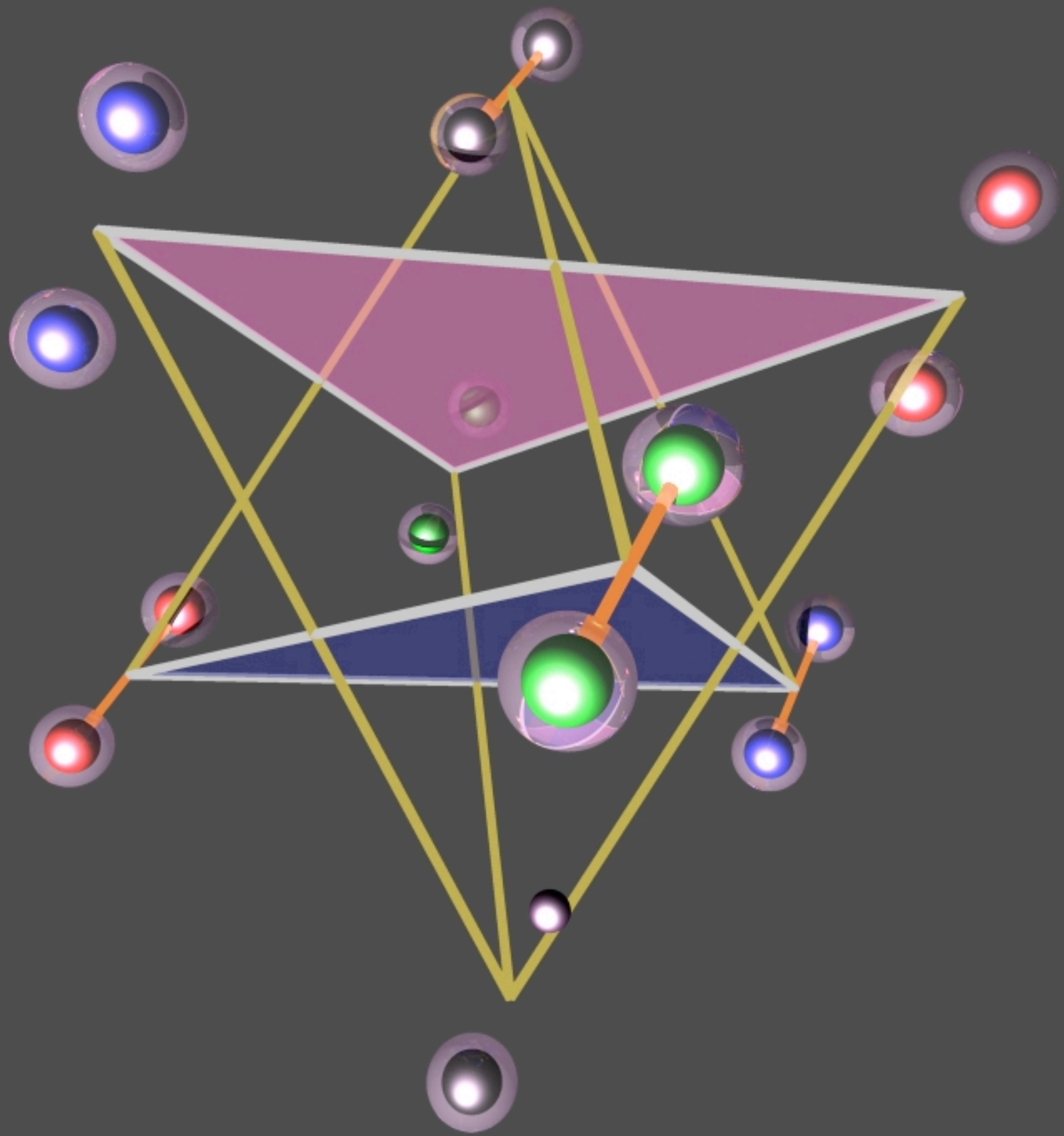












What would the world be like, if the

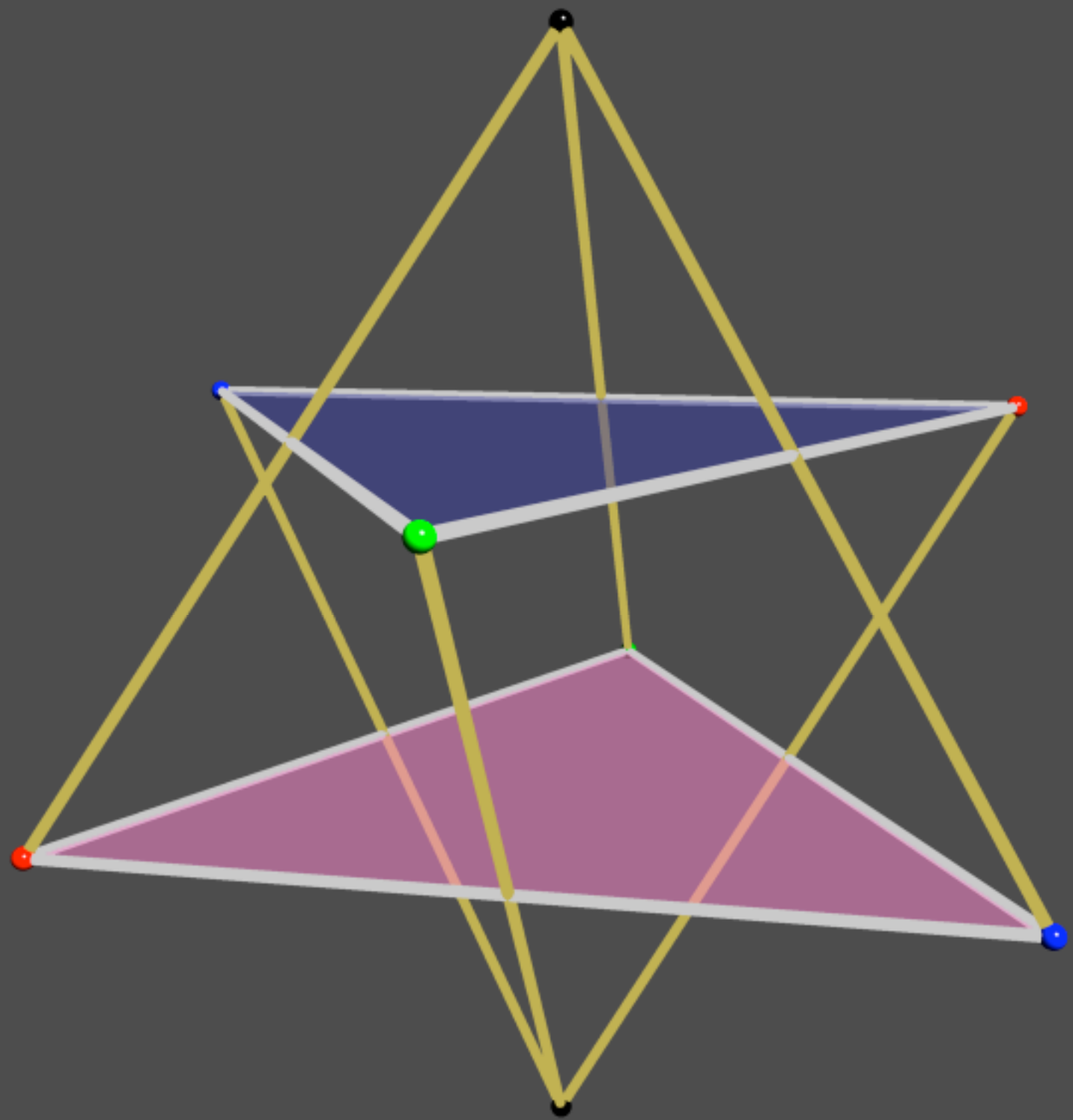
$$SU(2)_L \otimes U(1)_Y$$

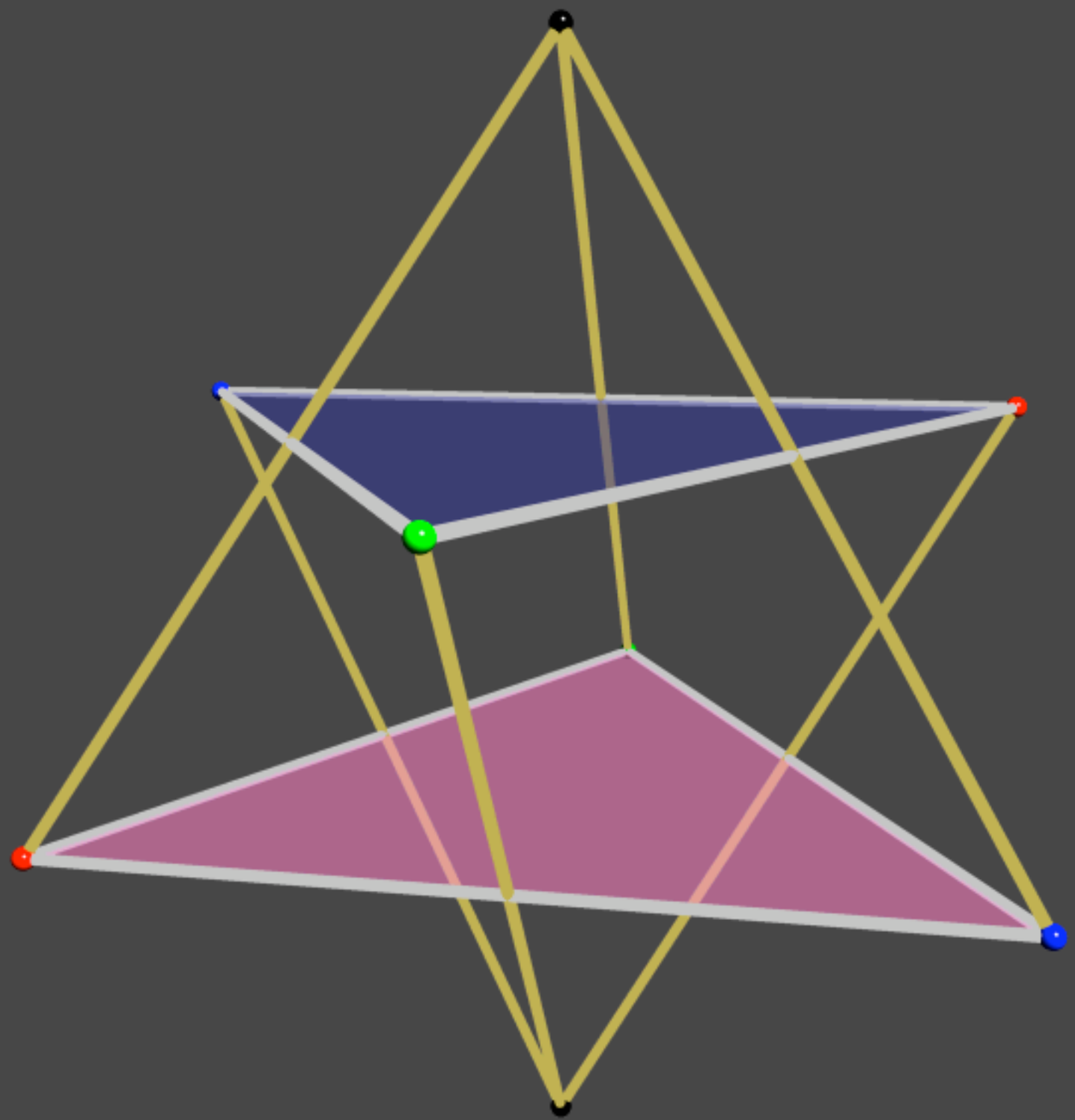
gauge symmetry were unbroken?

Consider the effects of *all* the

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

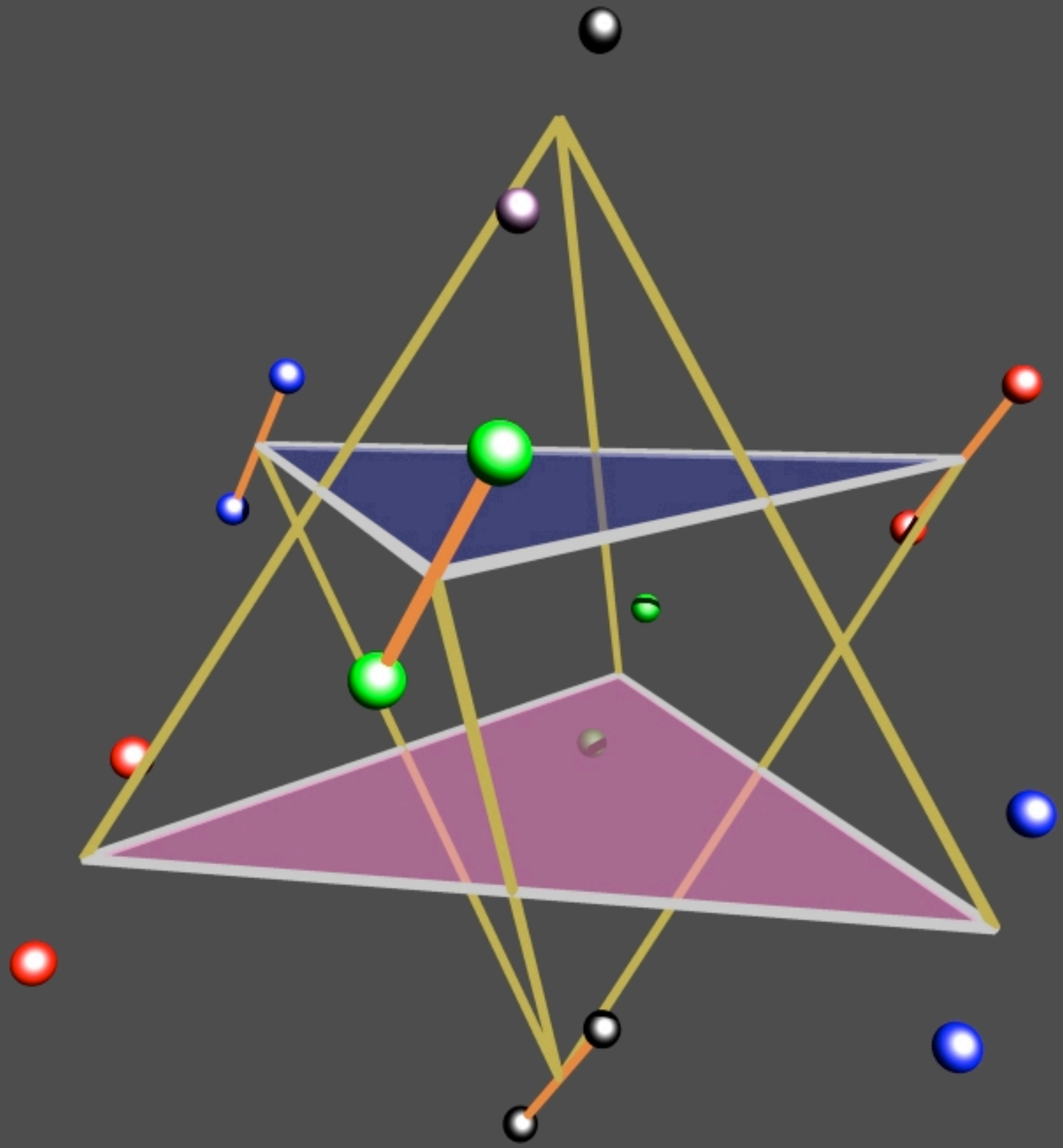
gauge fields.

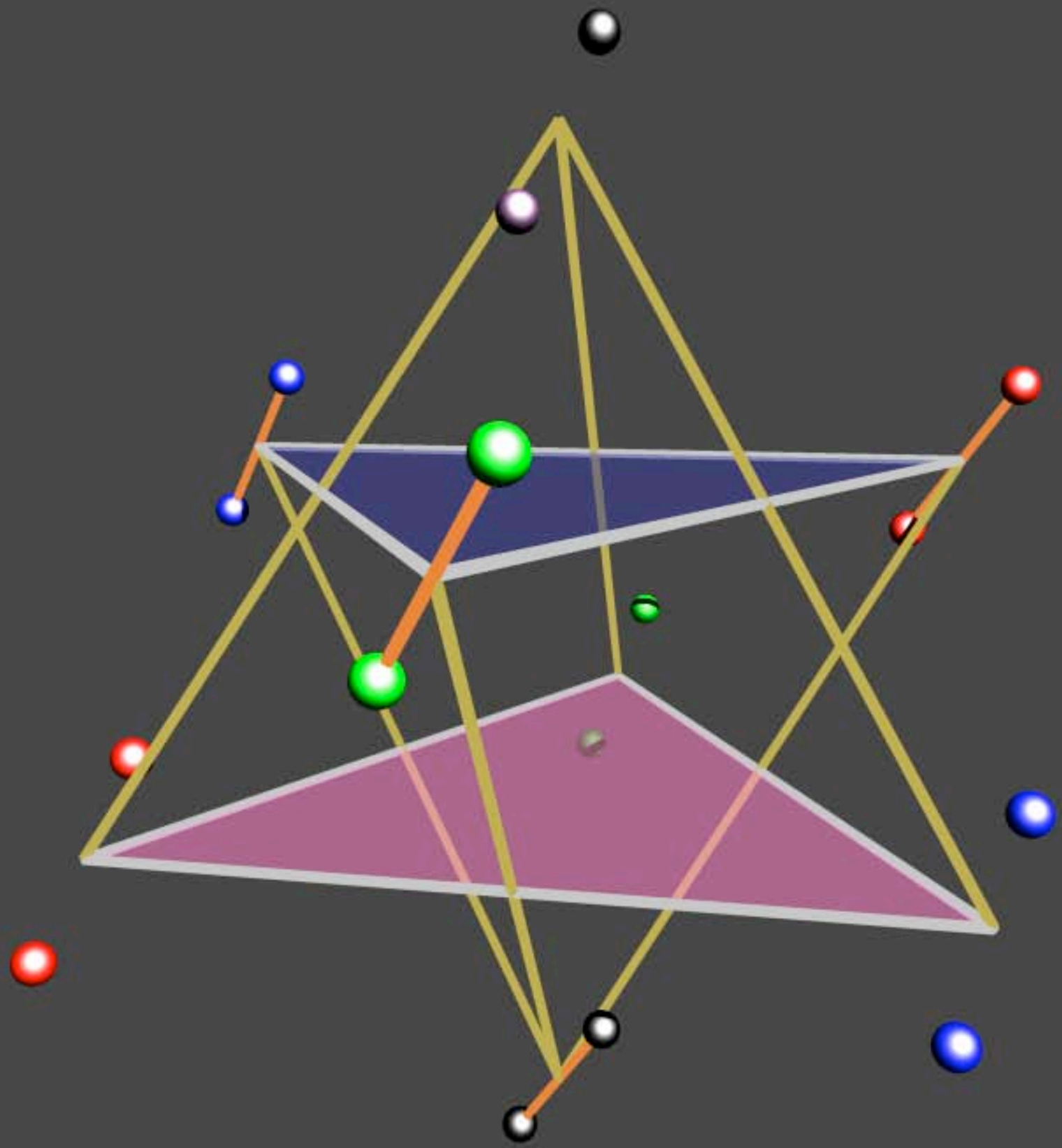


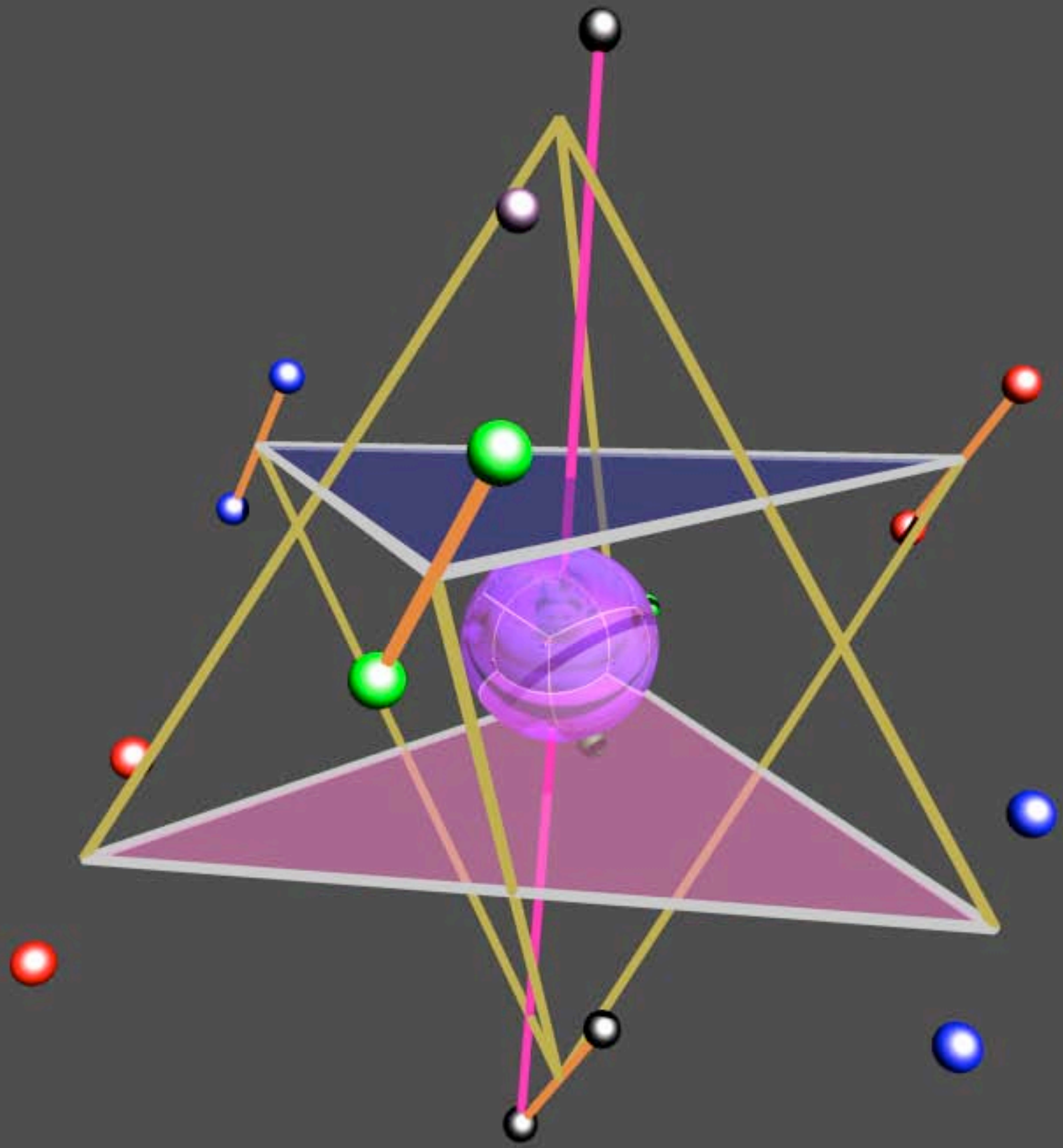


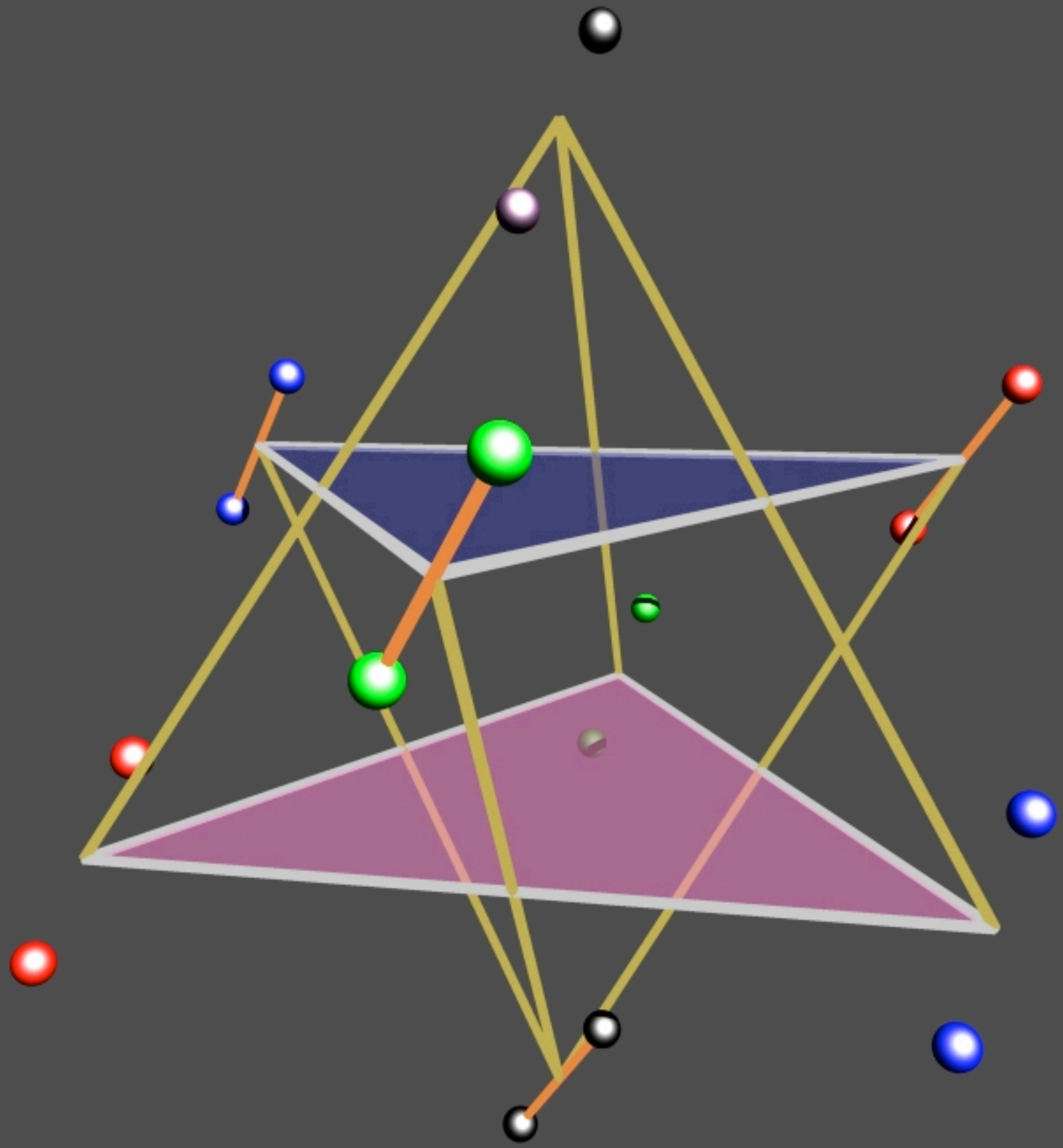
Mass terms connect LH & RH fermions

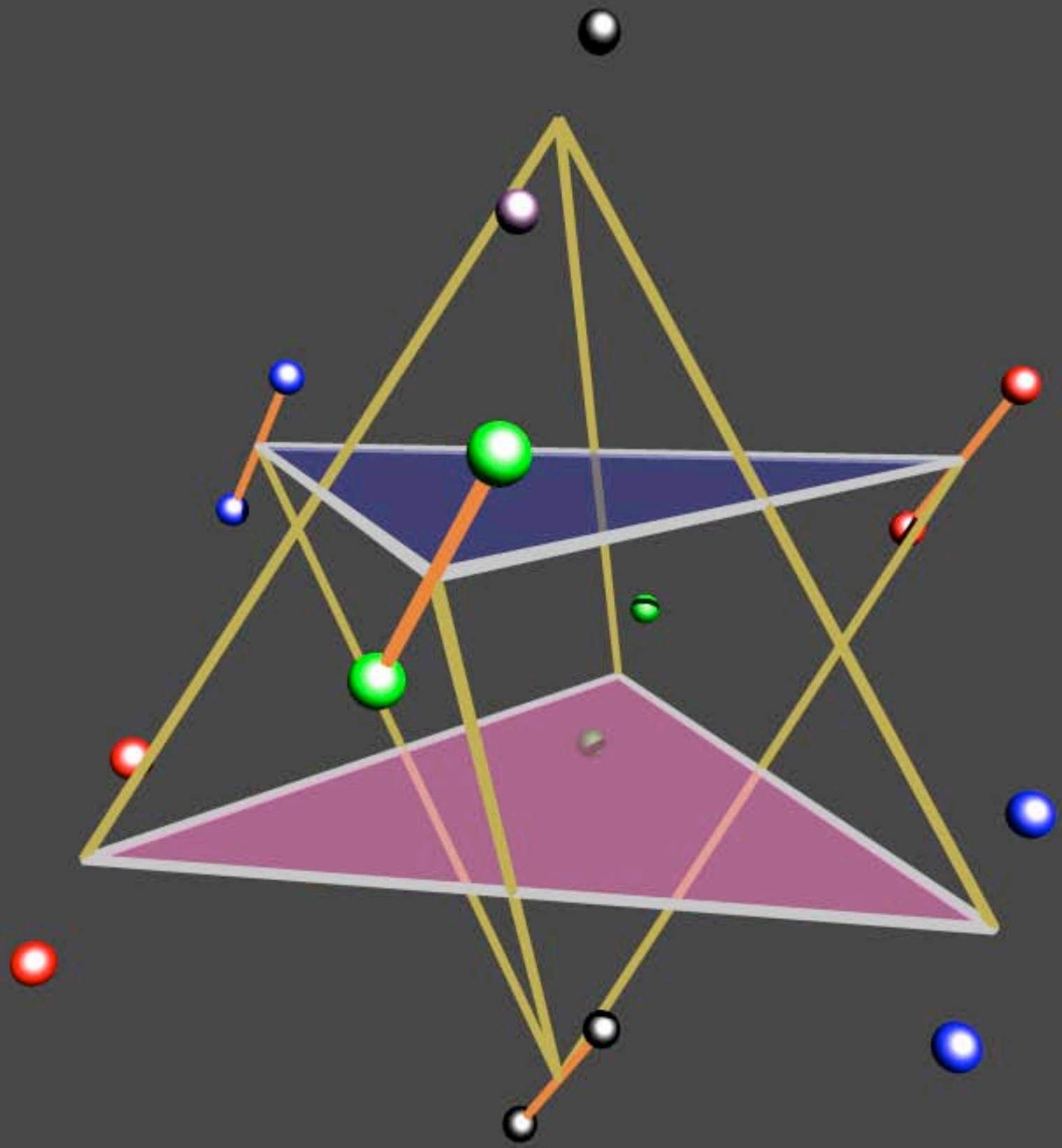
$$
\begin{aligned}
\mathcal{L}_e &= -m_e \bar{e} e \\
&= -m_e \bar{e} \left[\frac{(1-\gamma_5)}{2} + \frac{(1+\gamma_5)}{2} \right] e \\
&= -m_e \left(\bar{e}_R e_L + \bar{e}_L e_R \right)
\end{aligned}
$$

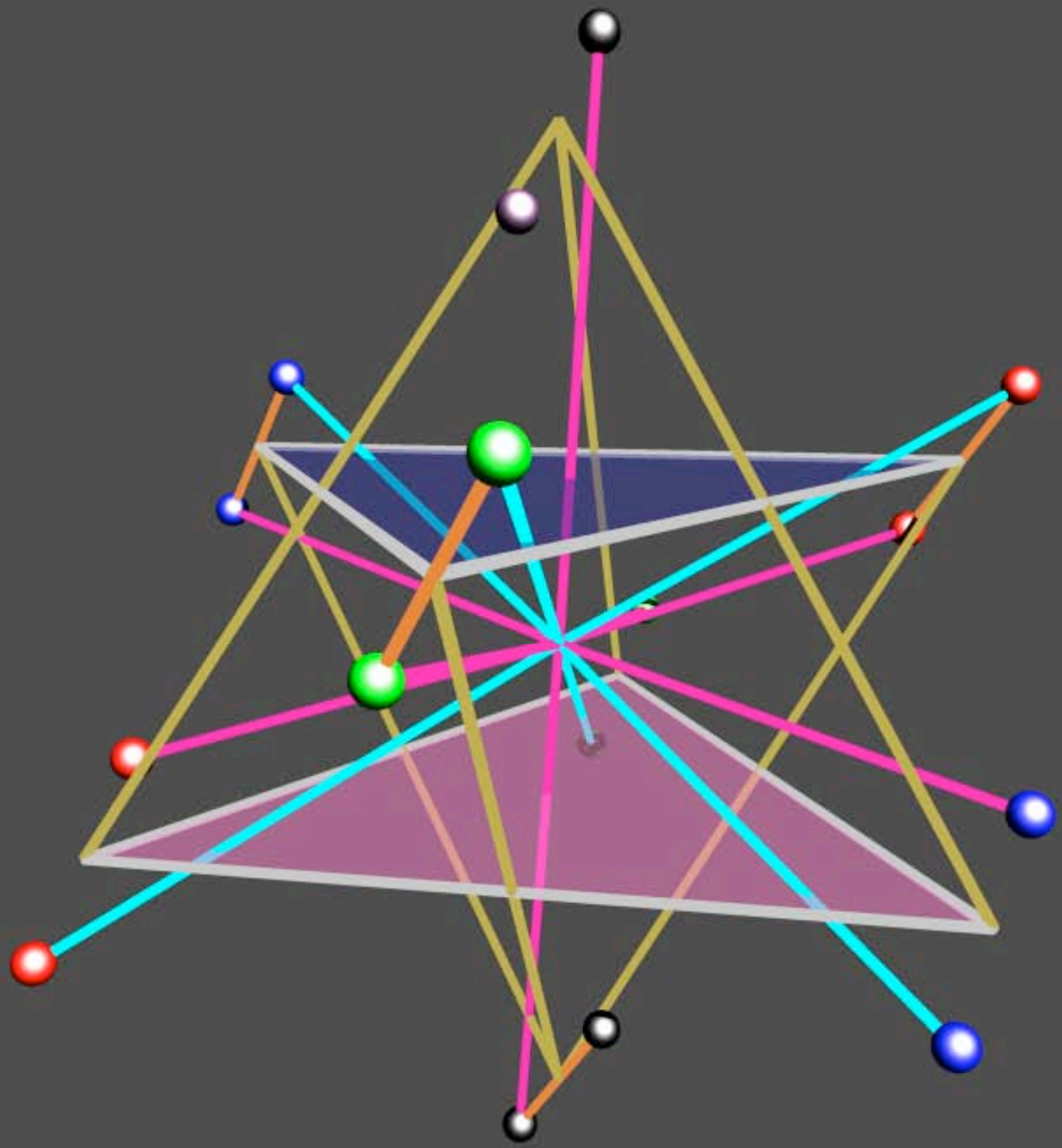


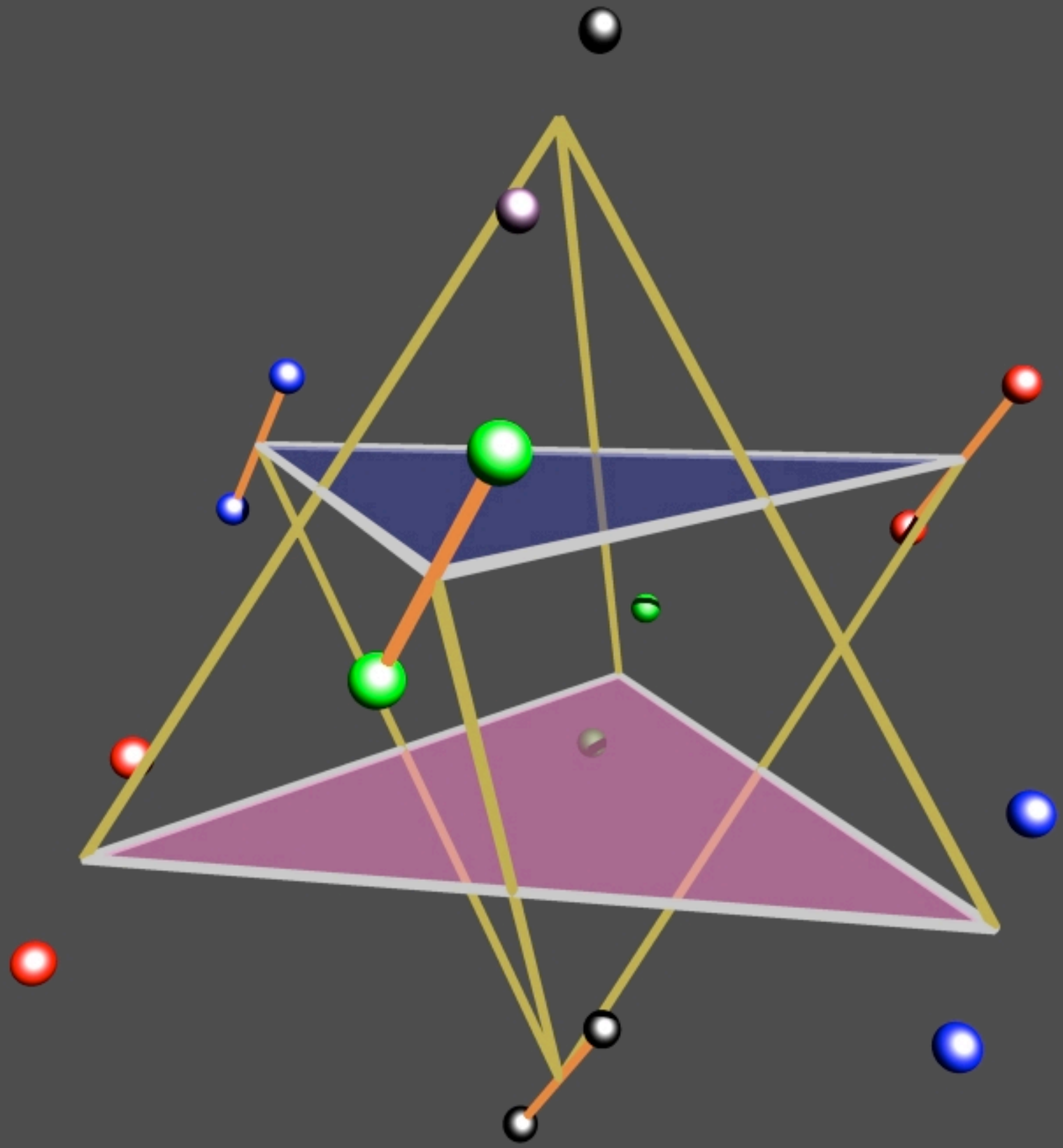


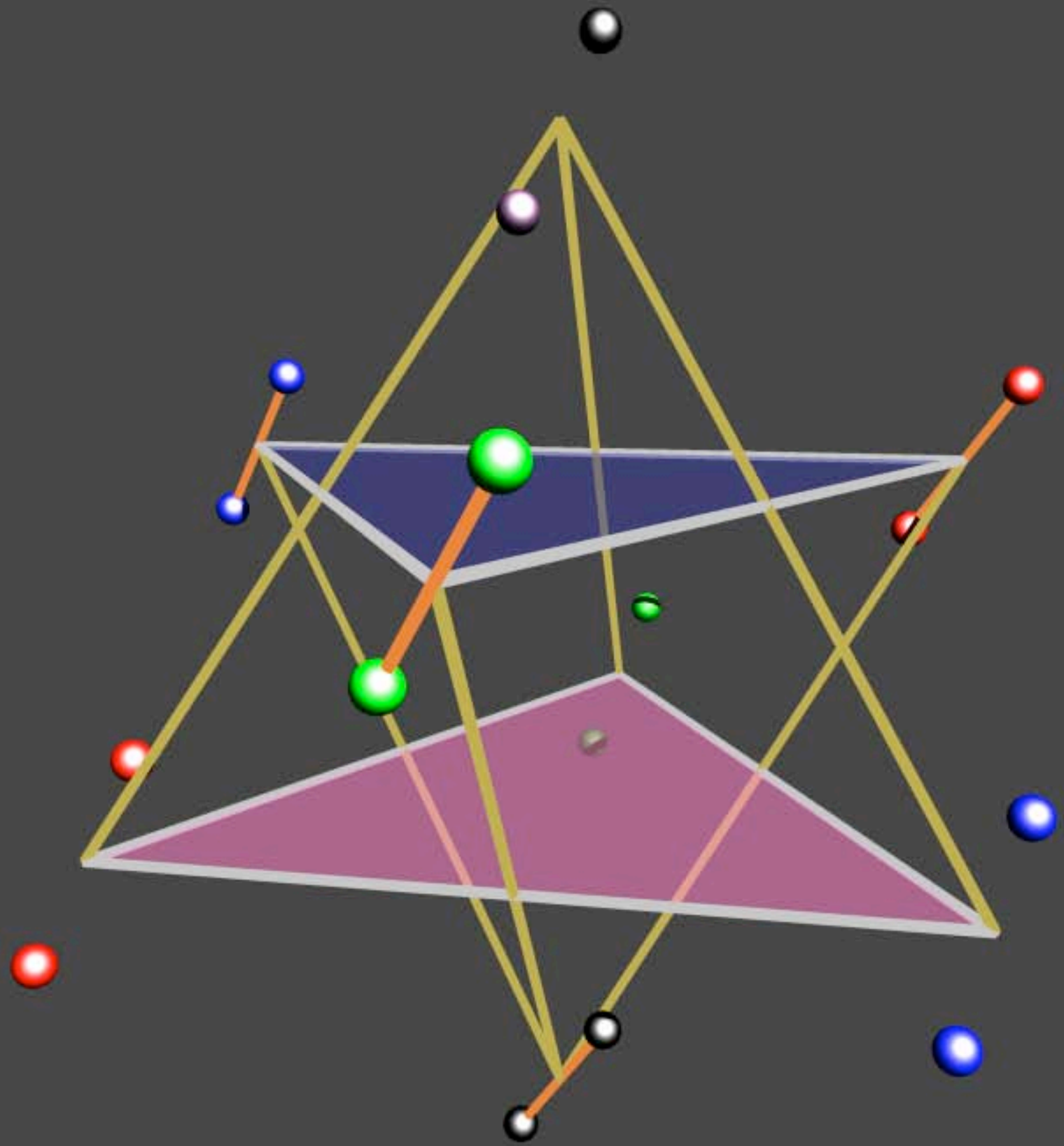


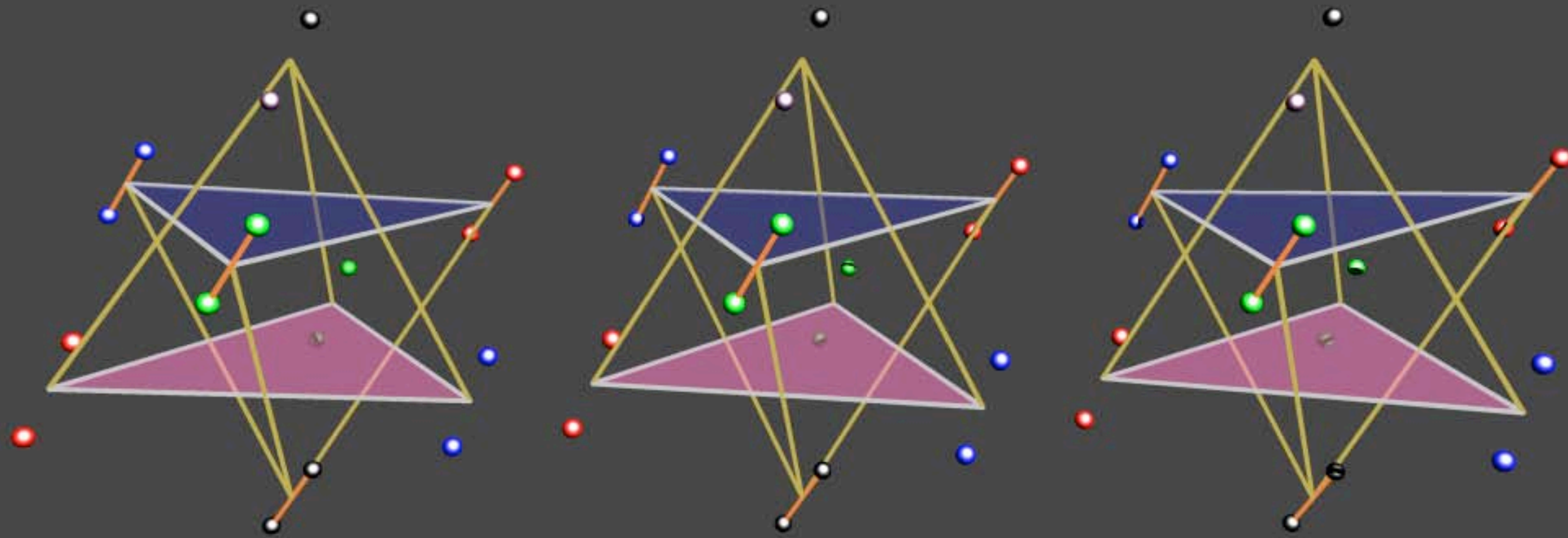


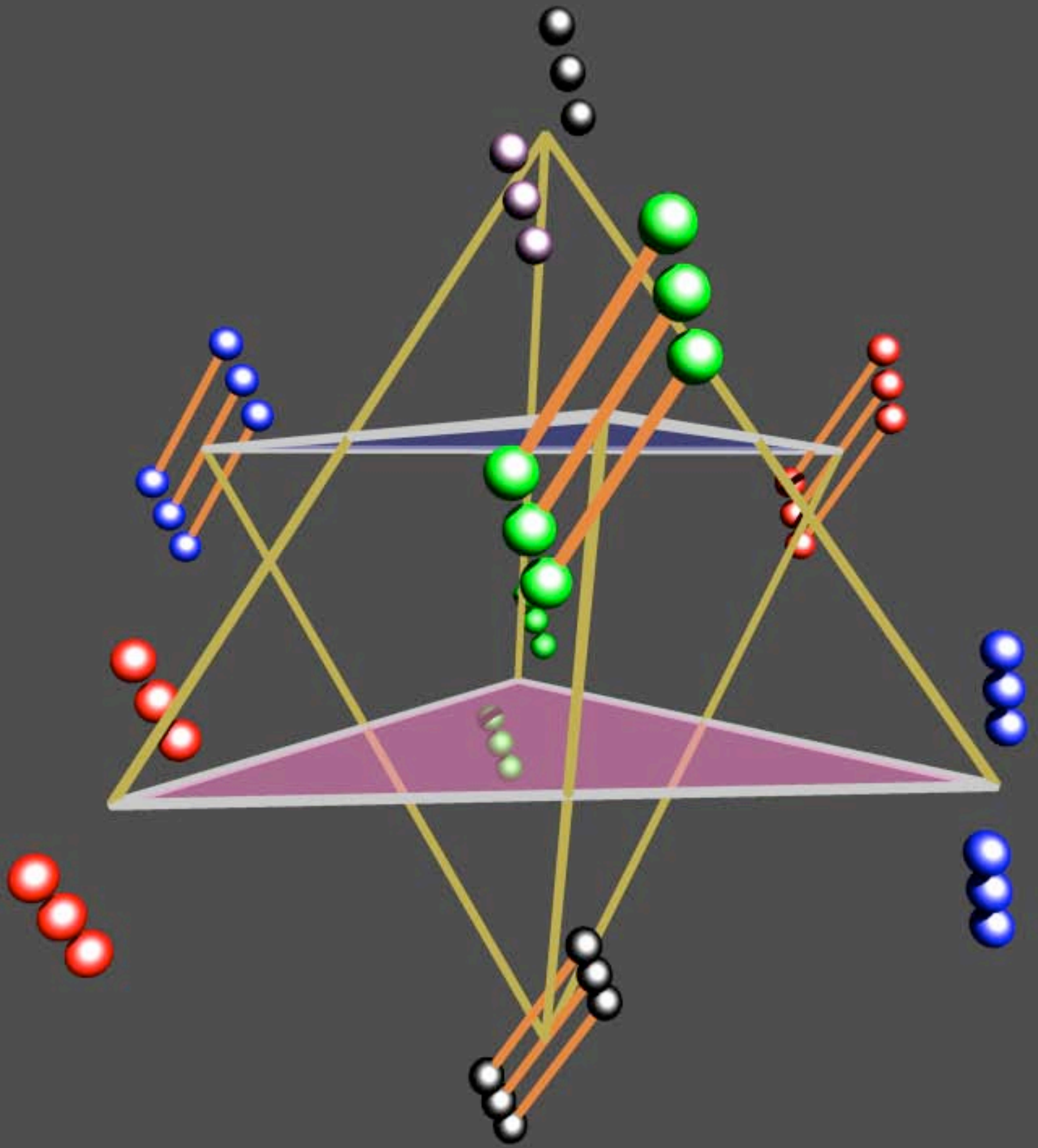


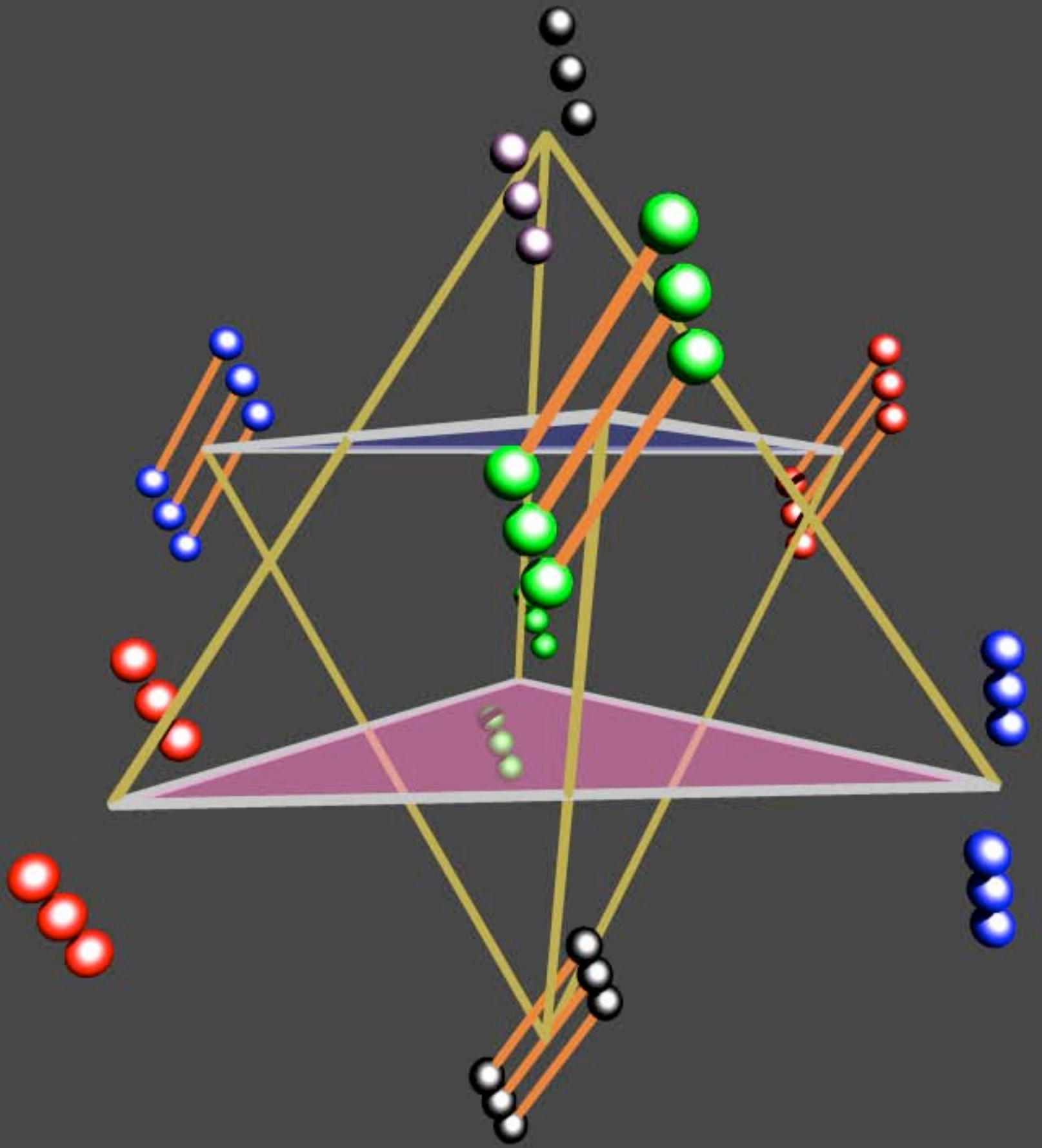


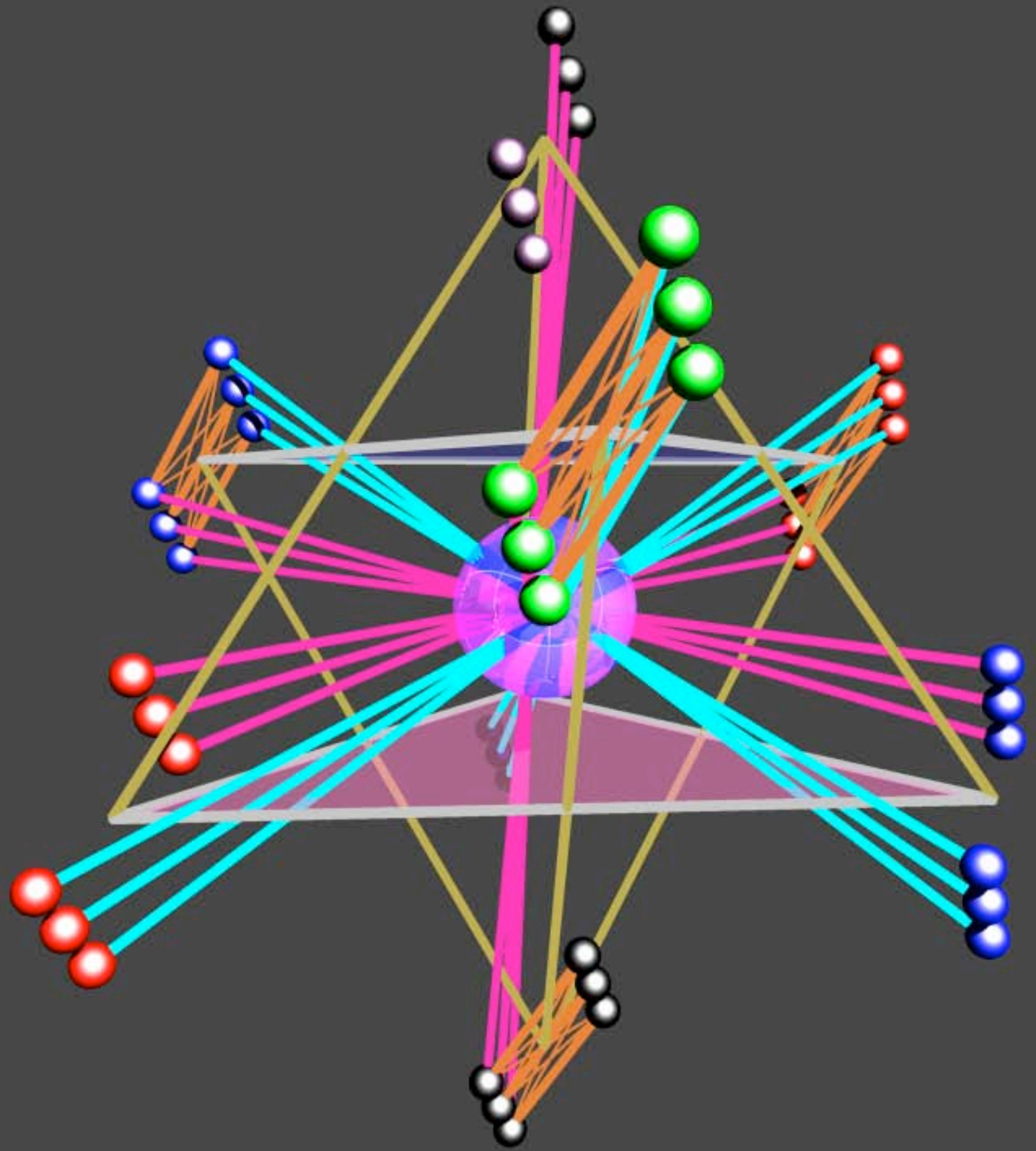


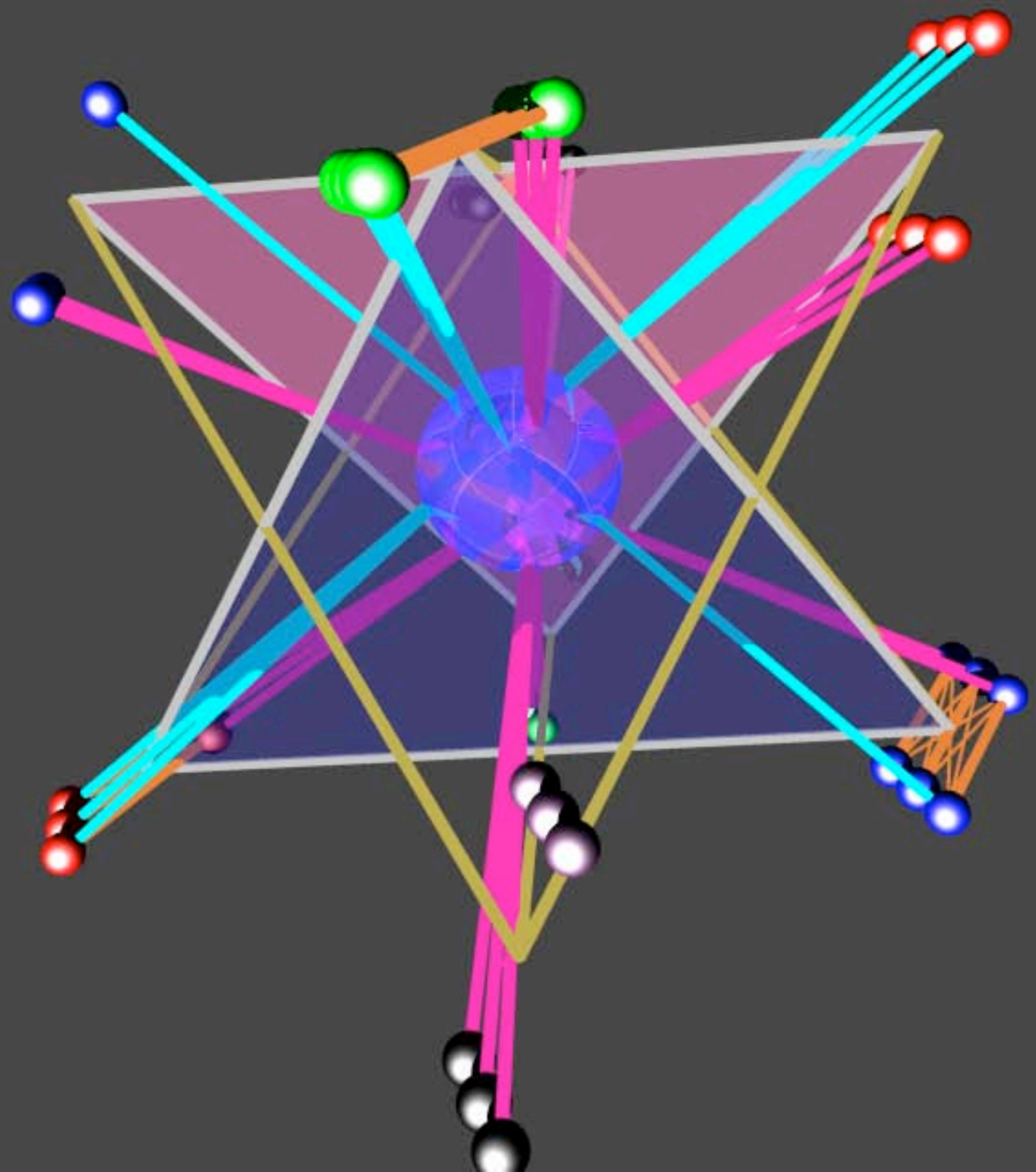


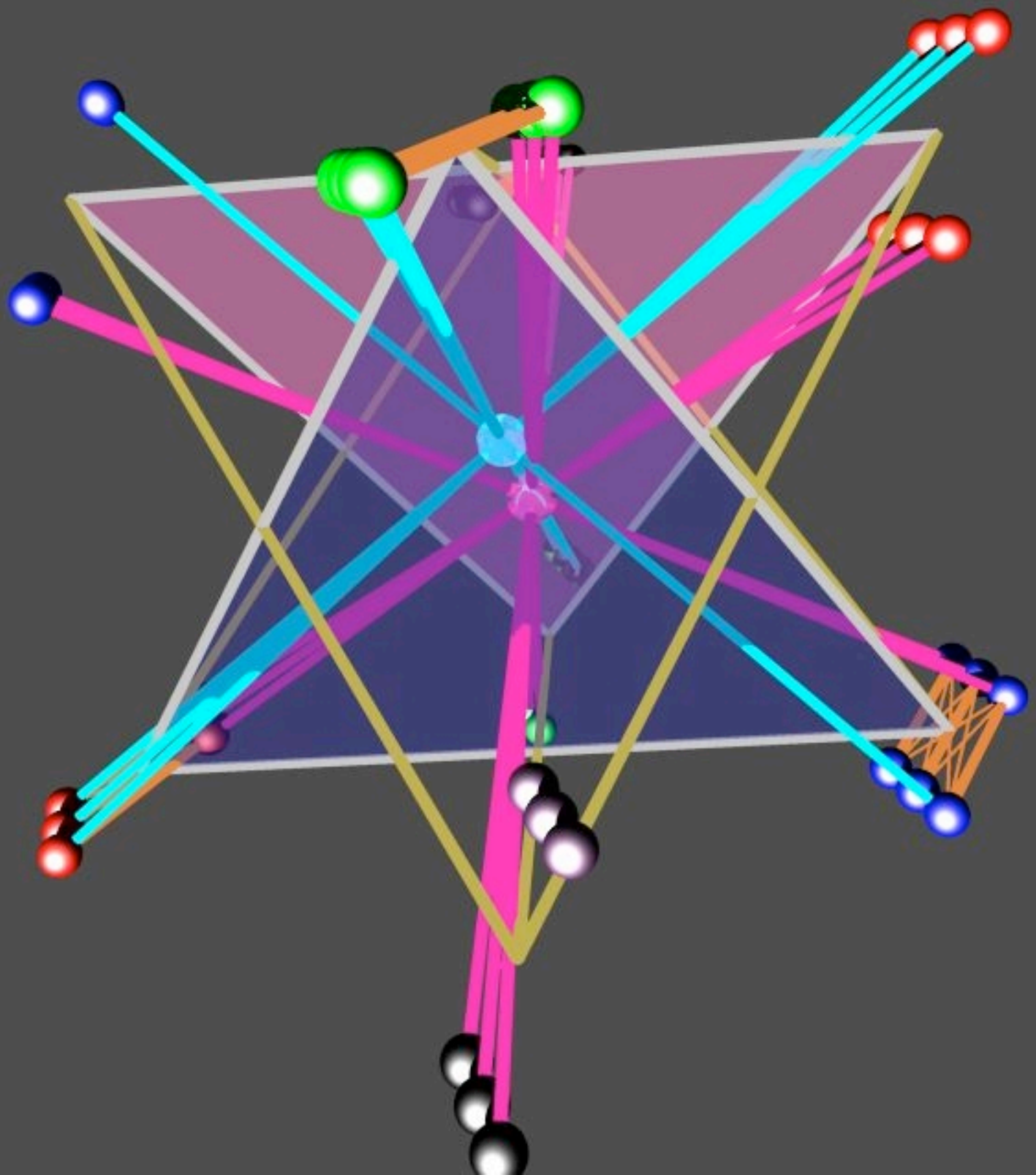


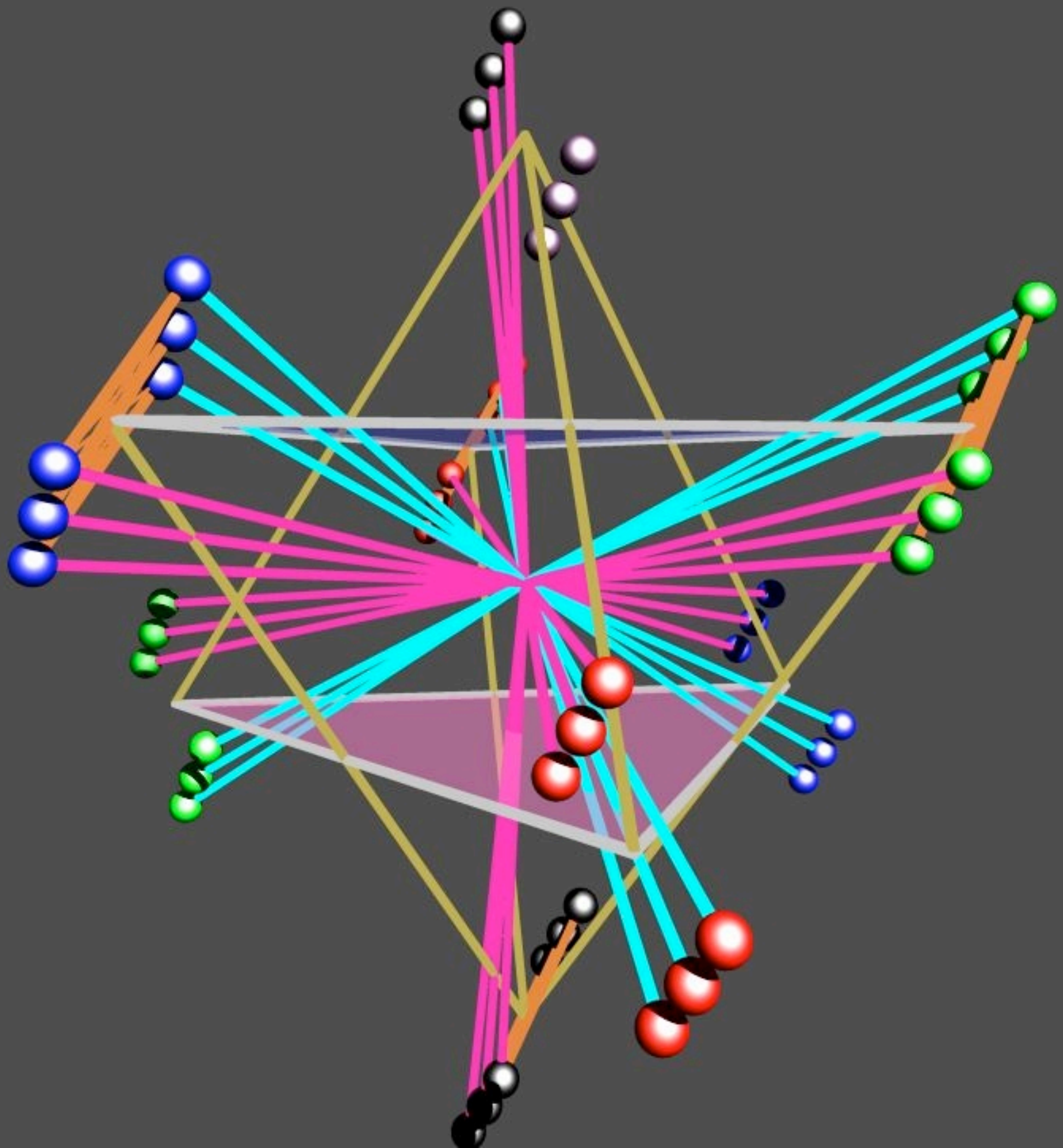


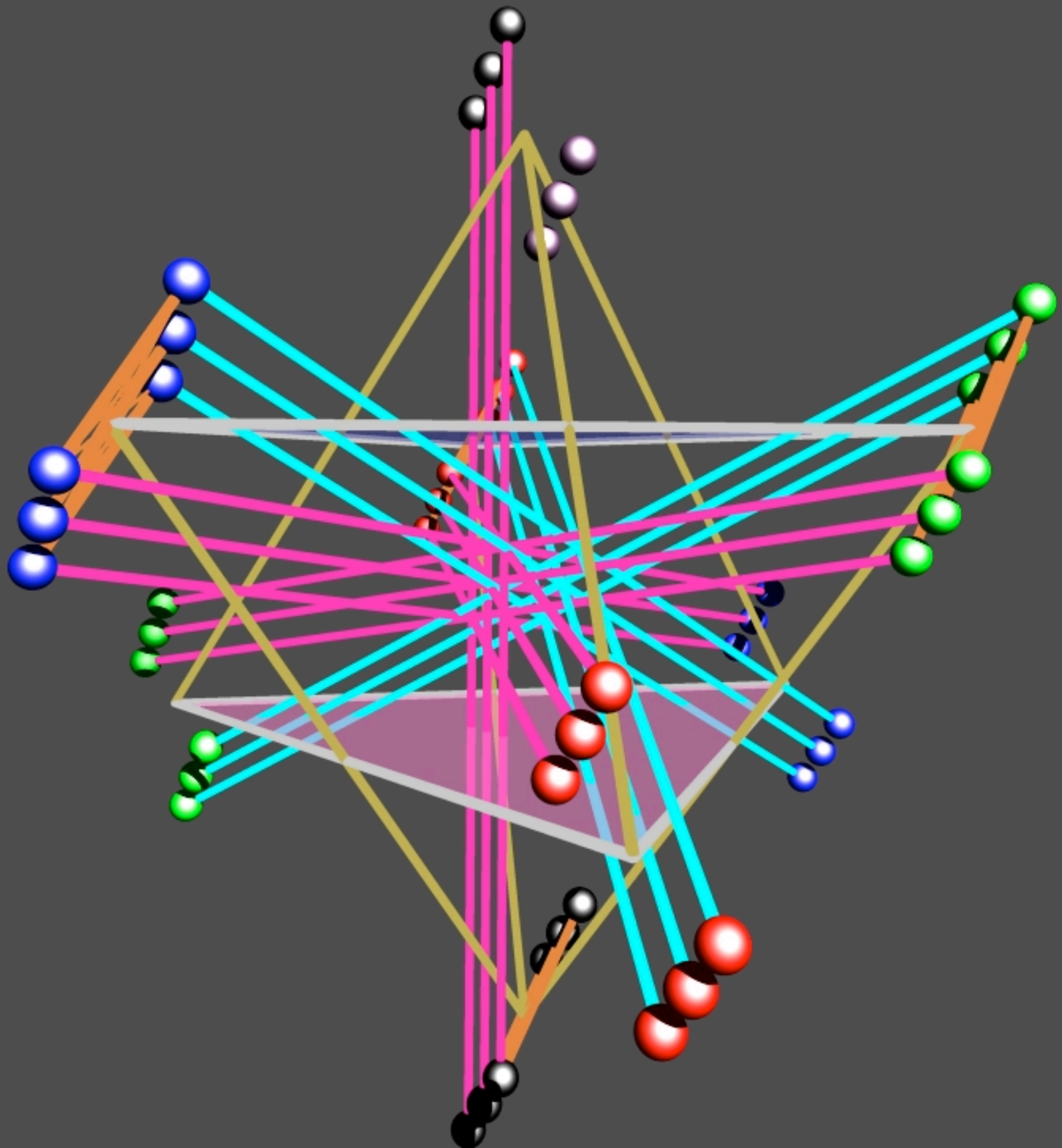


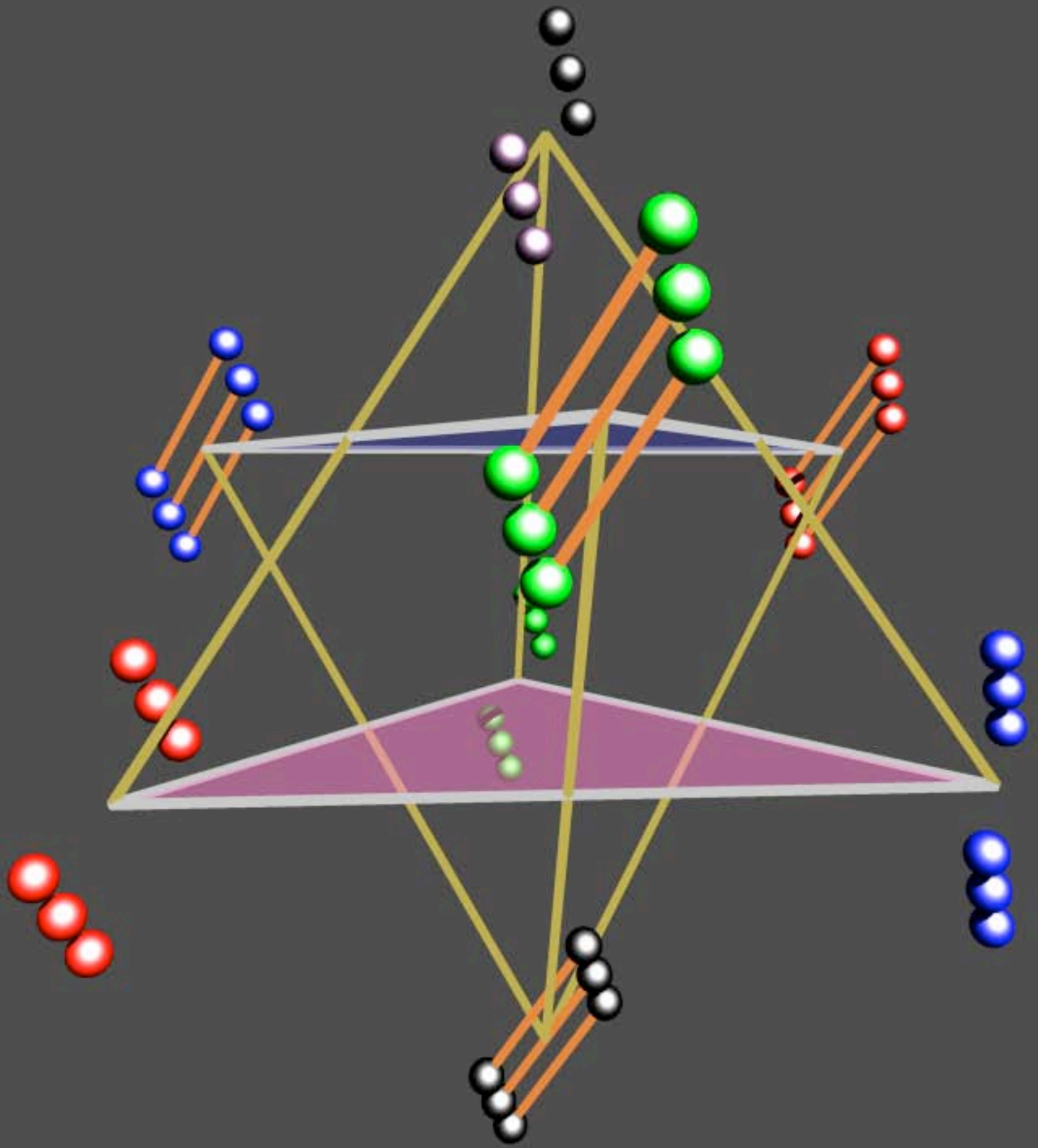


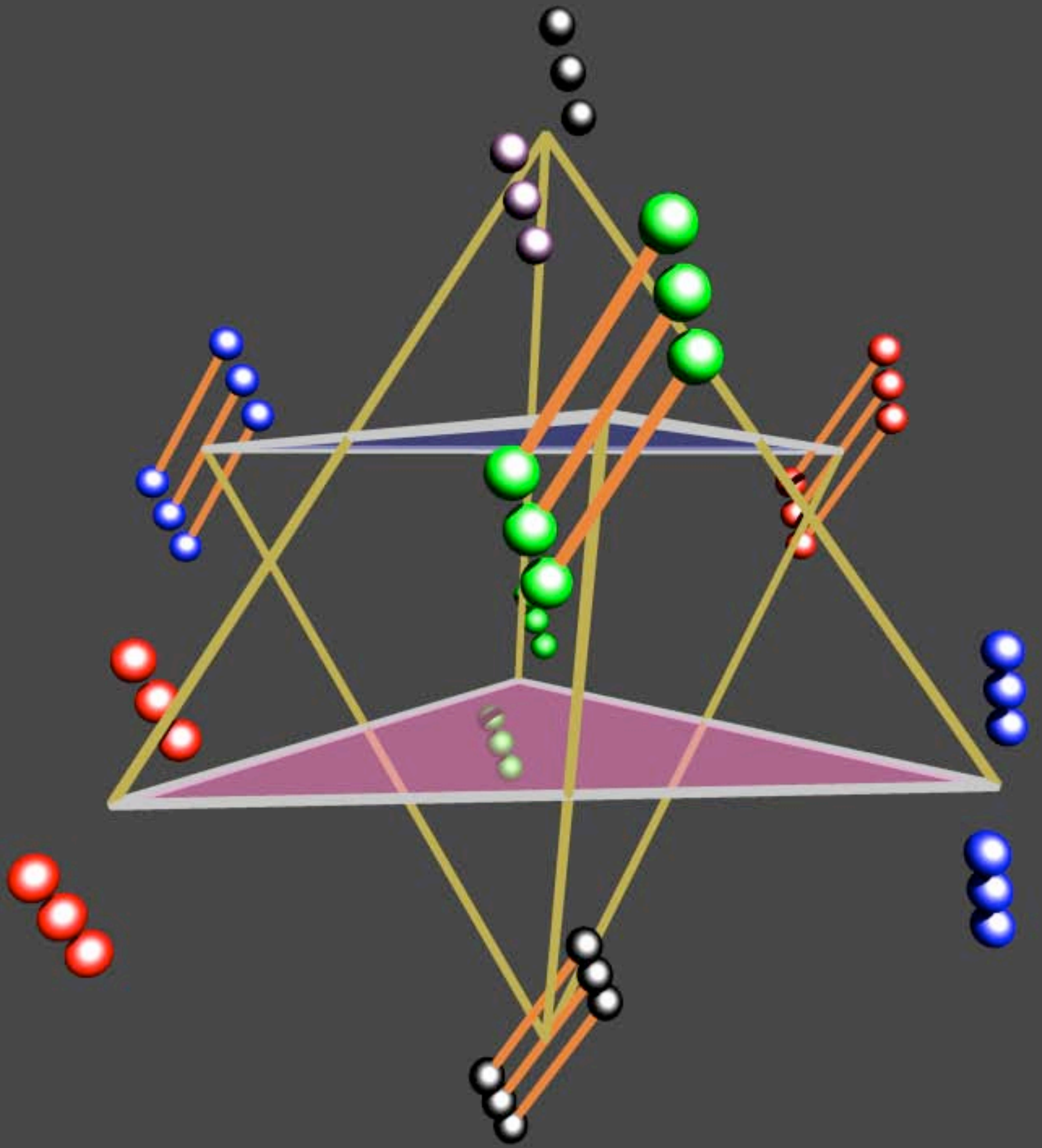












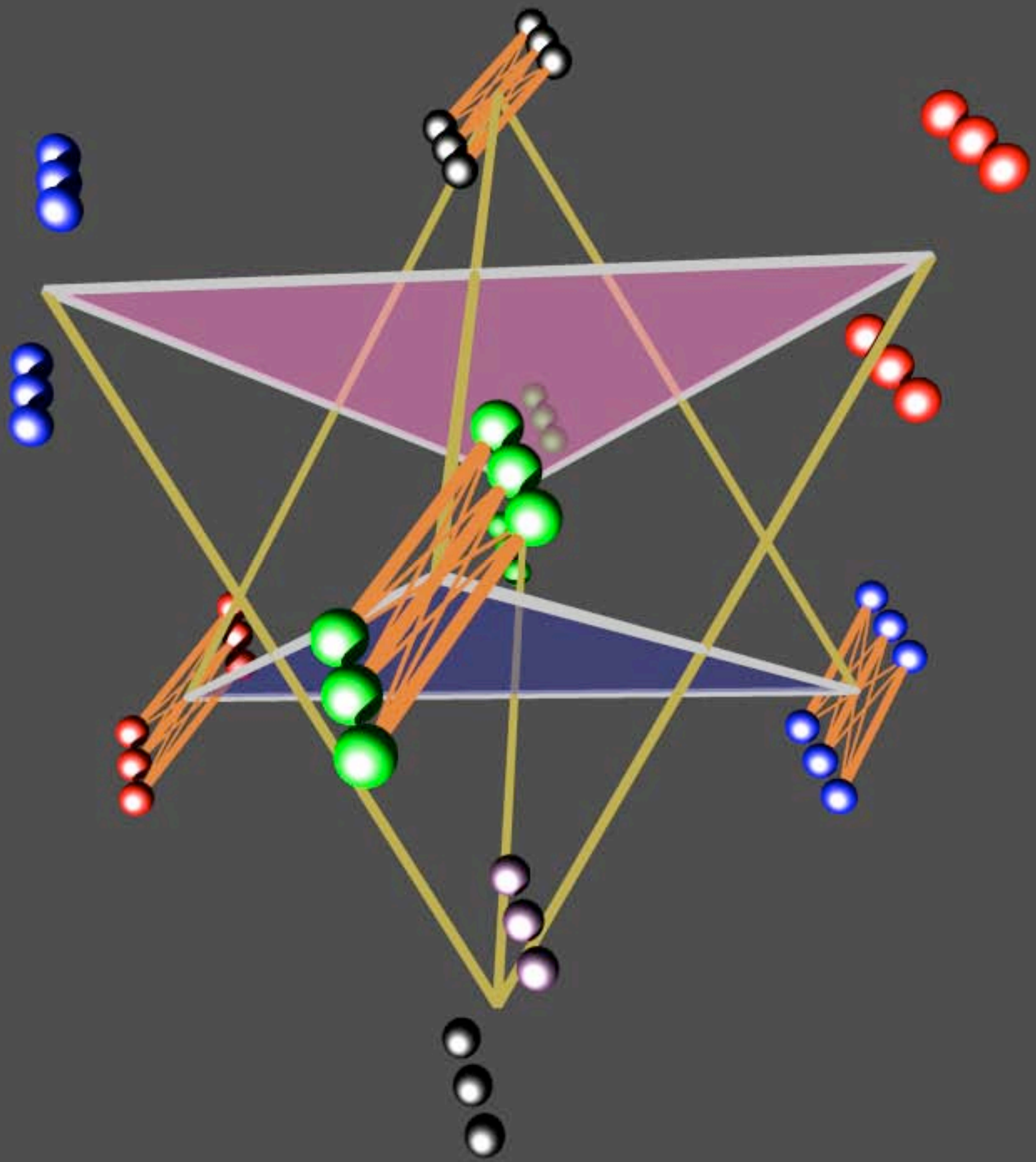
Basis of the double simplex:

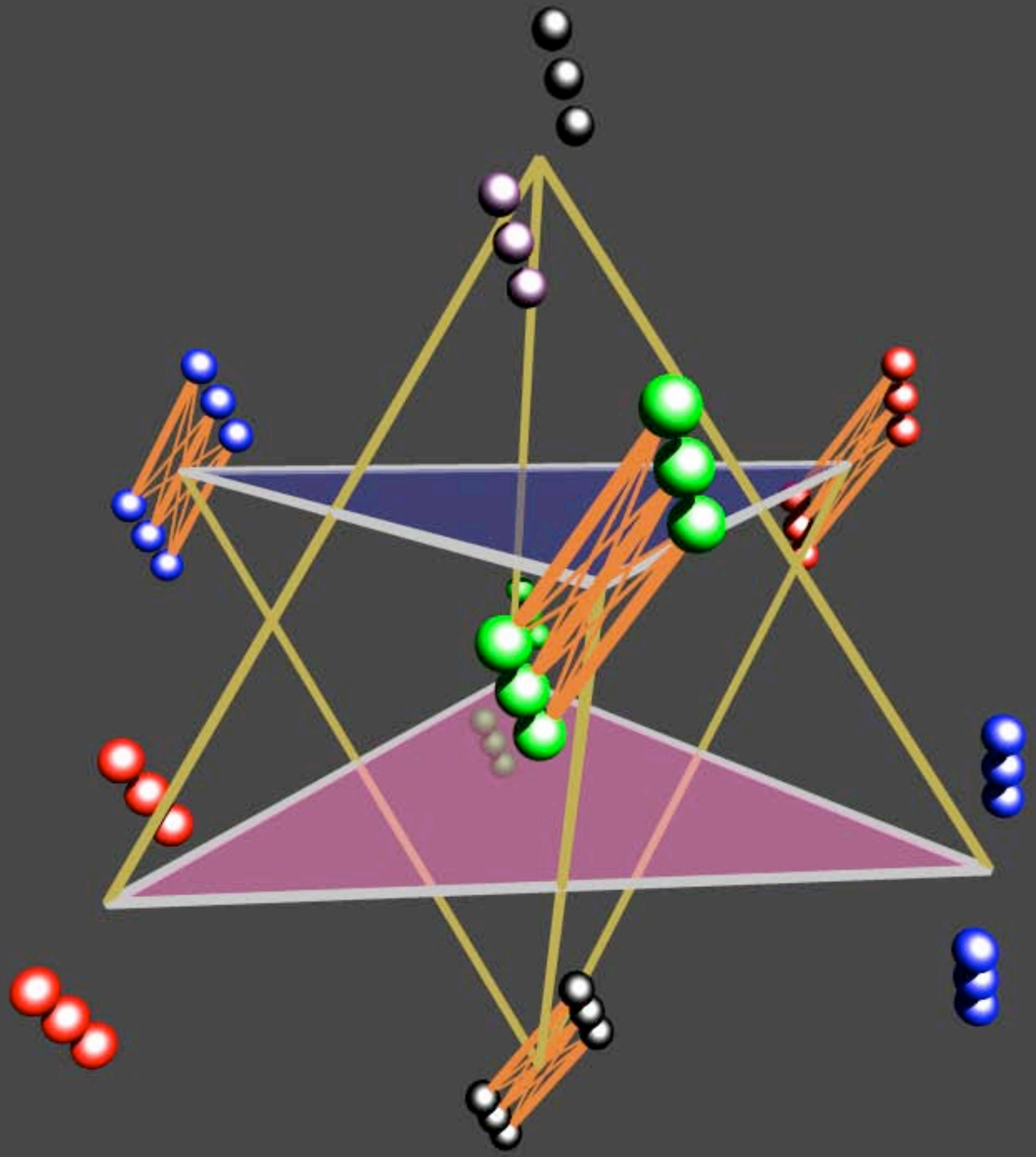
$$SO(10) \to SU(4) \otimes SU(2) \otimes SU(2)$$

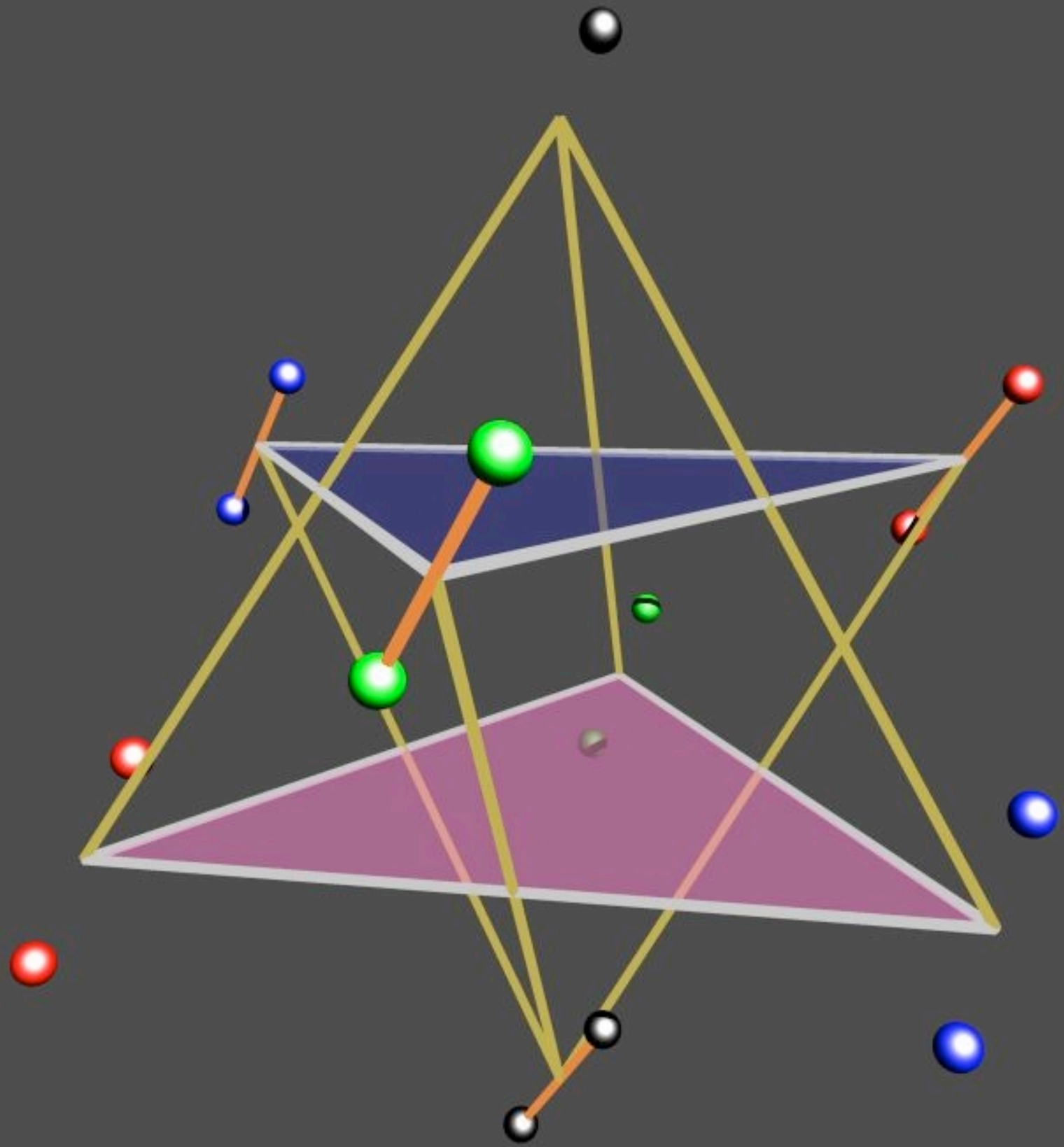
Lepton number as 4th color

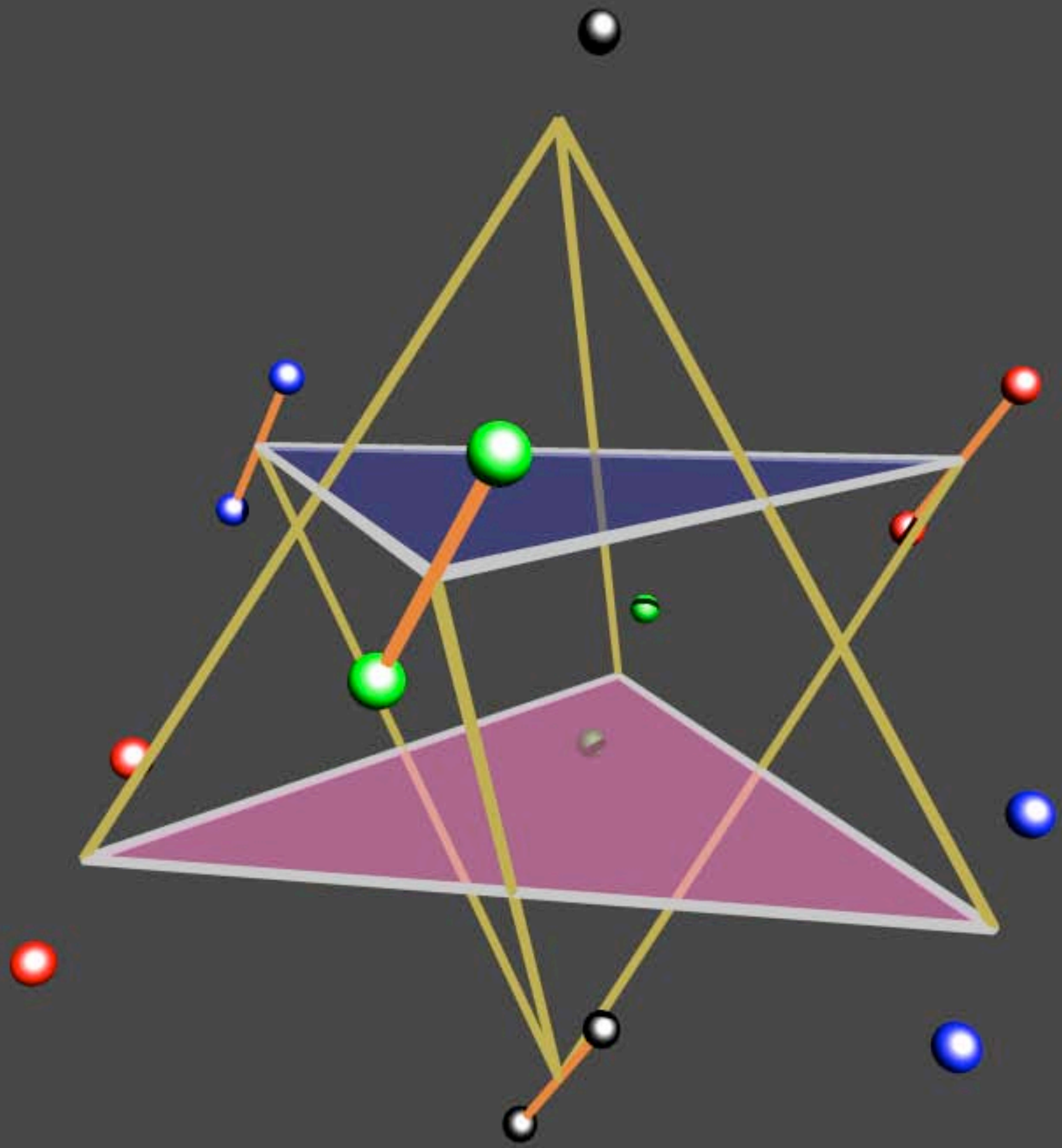
B – *L* along vertical

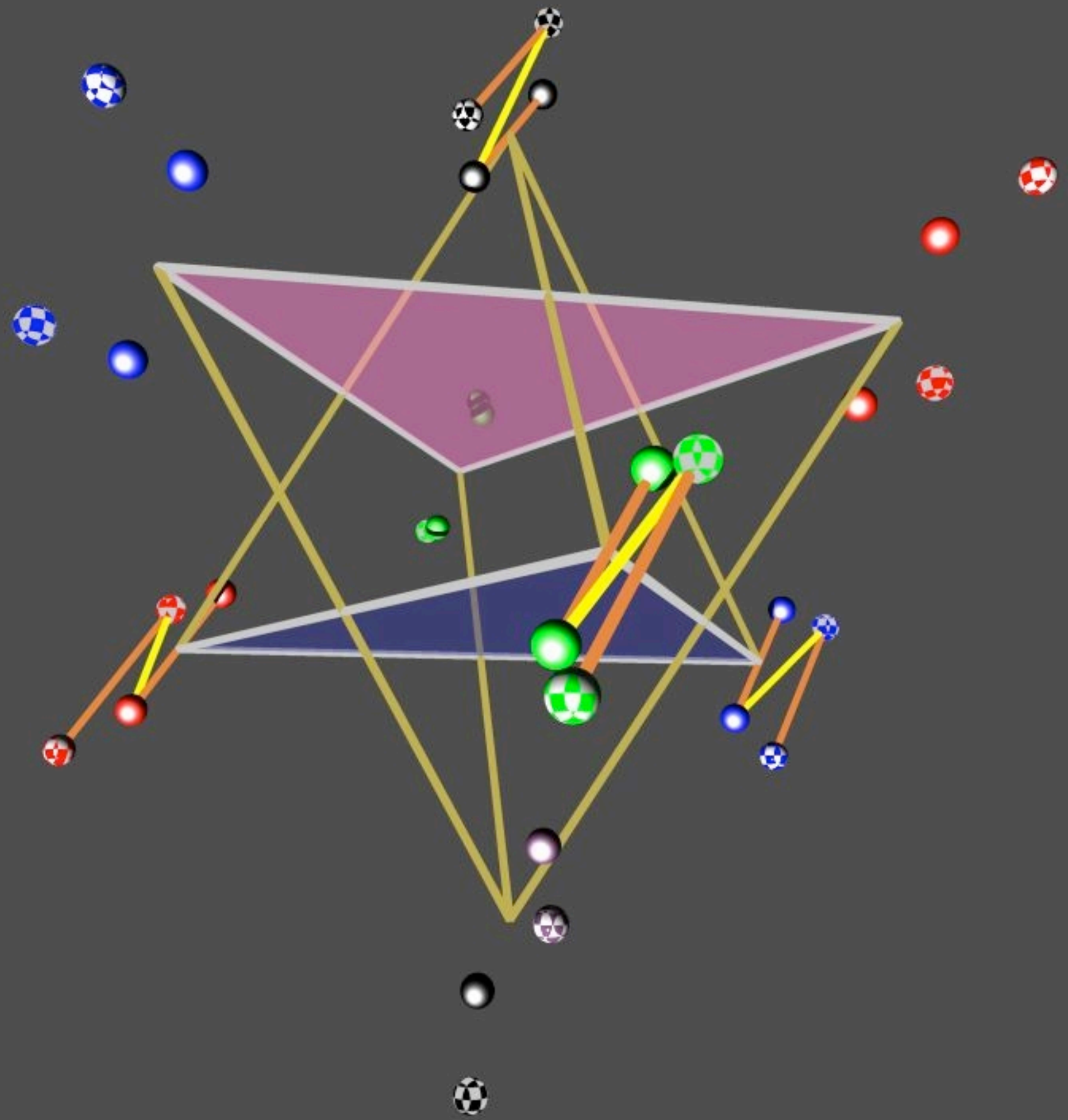
LH, RH decorations at vertices

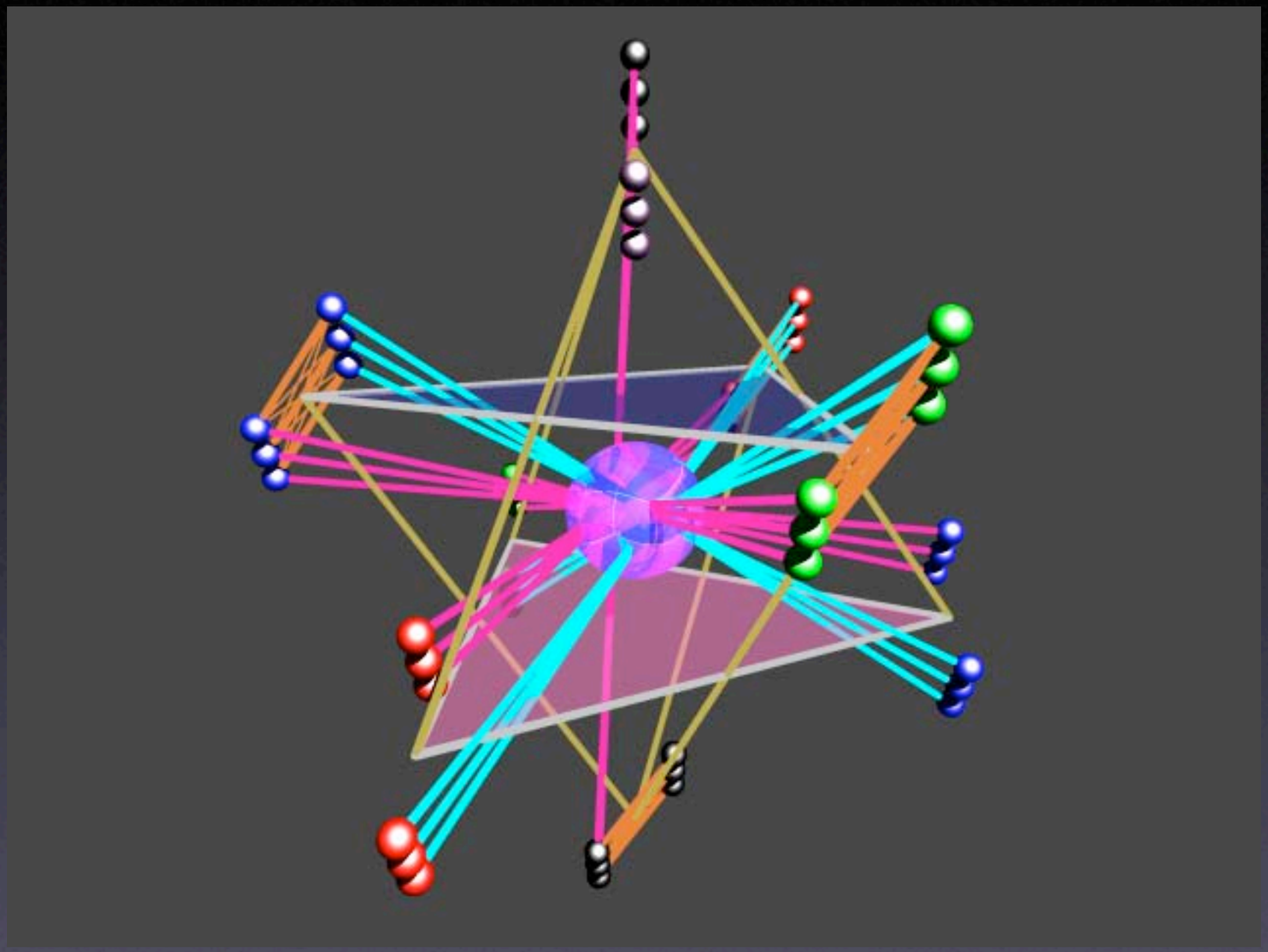


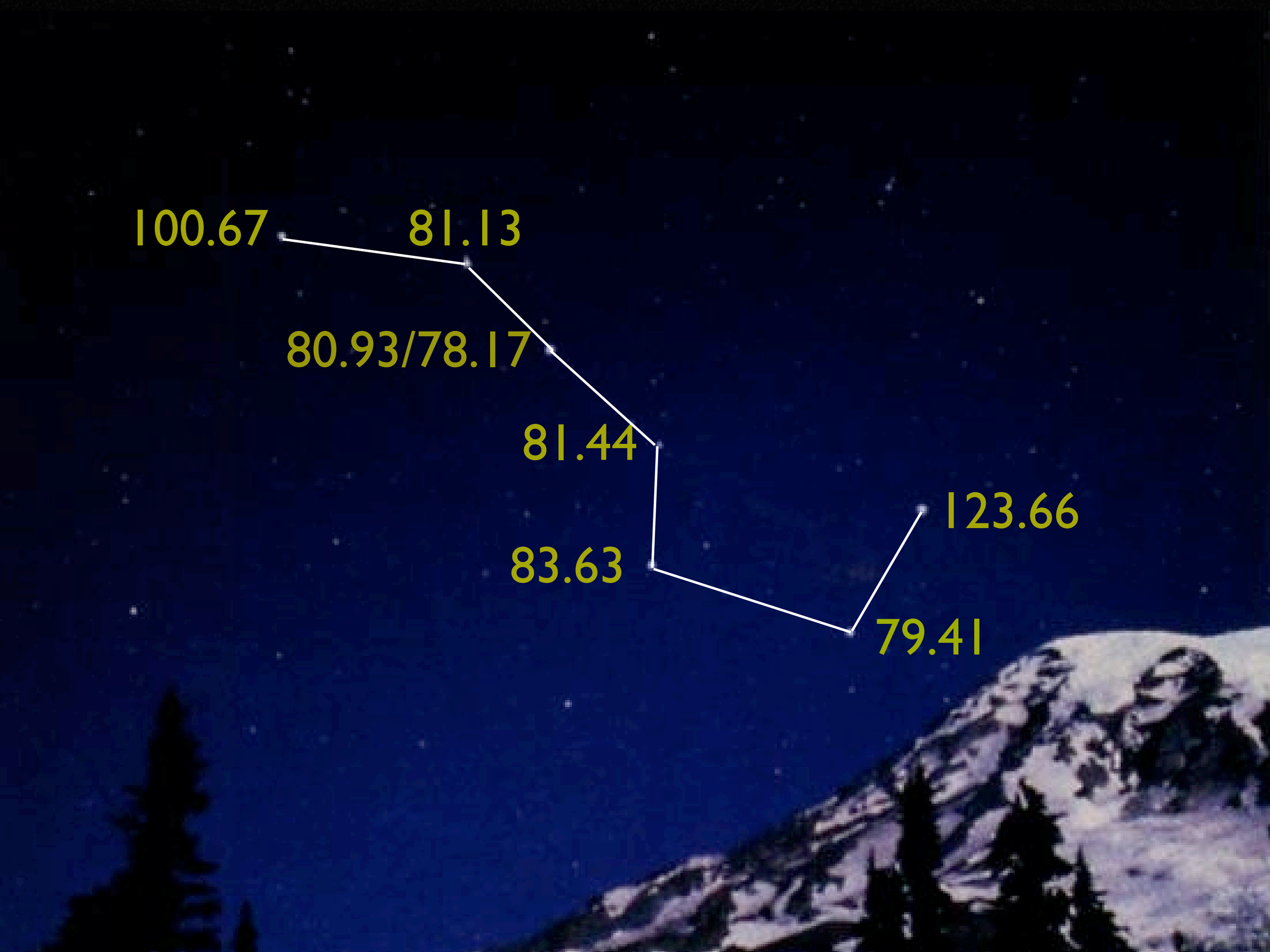








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80.93/78.17
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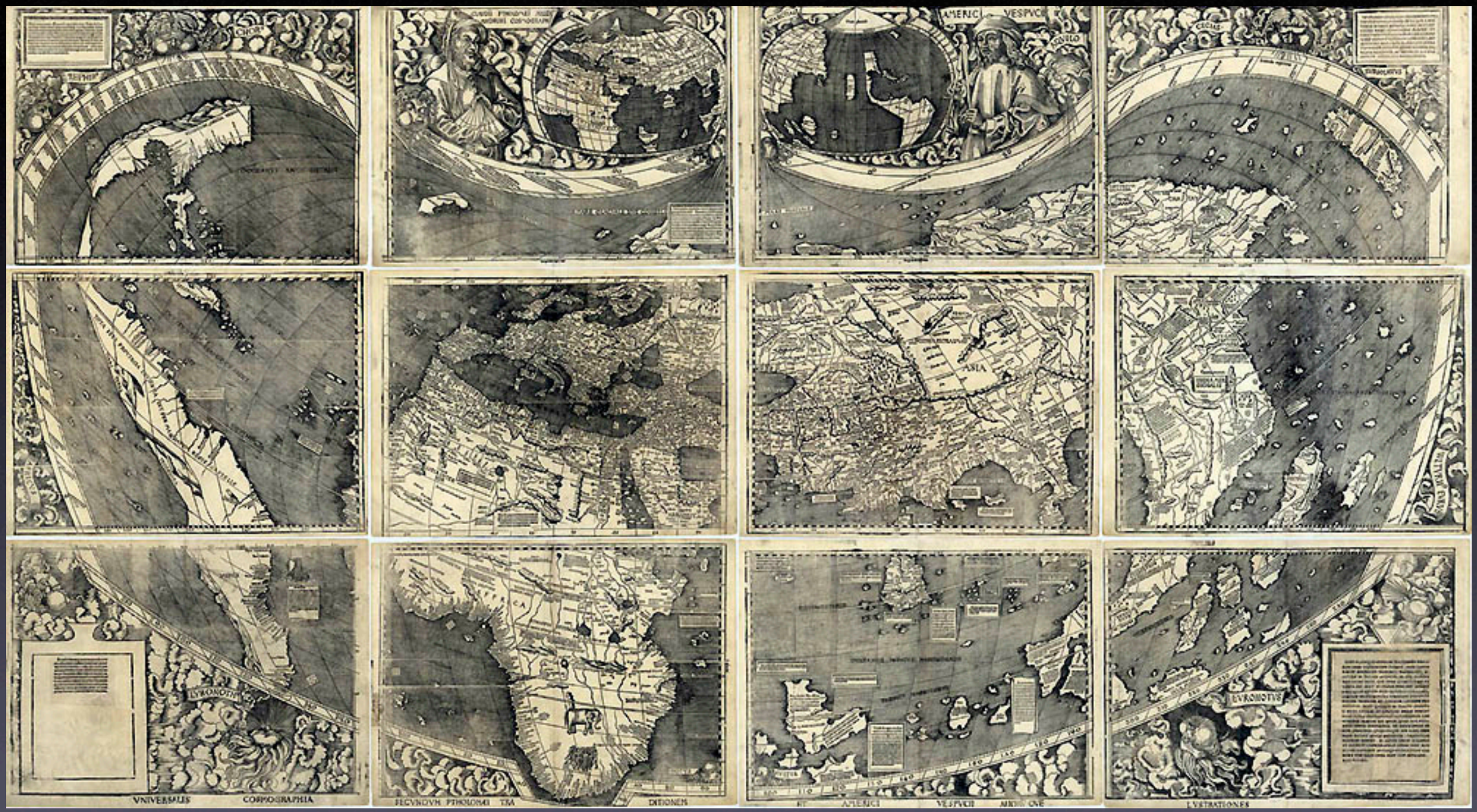
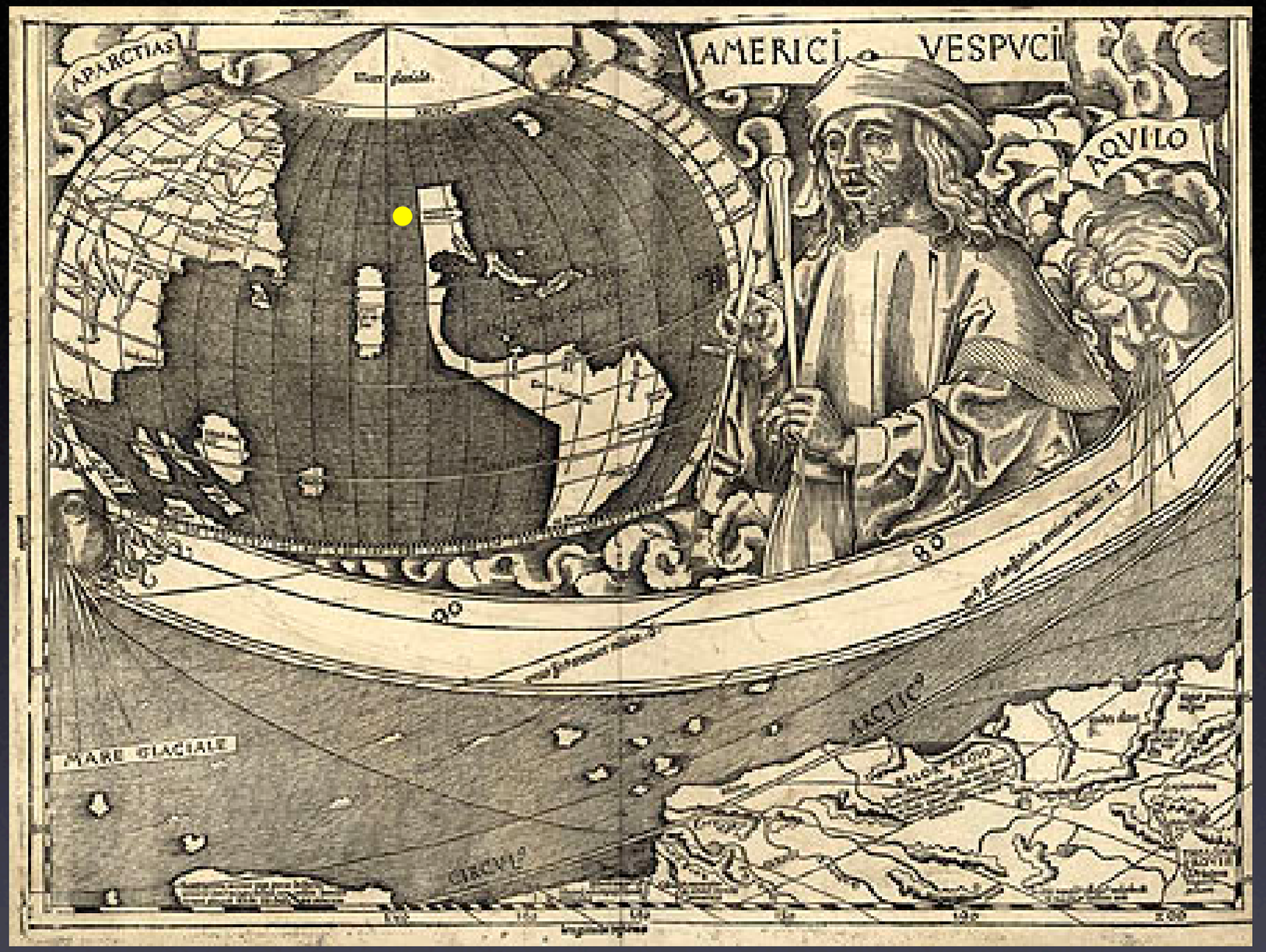
83.63
79.41

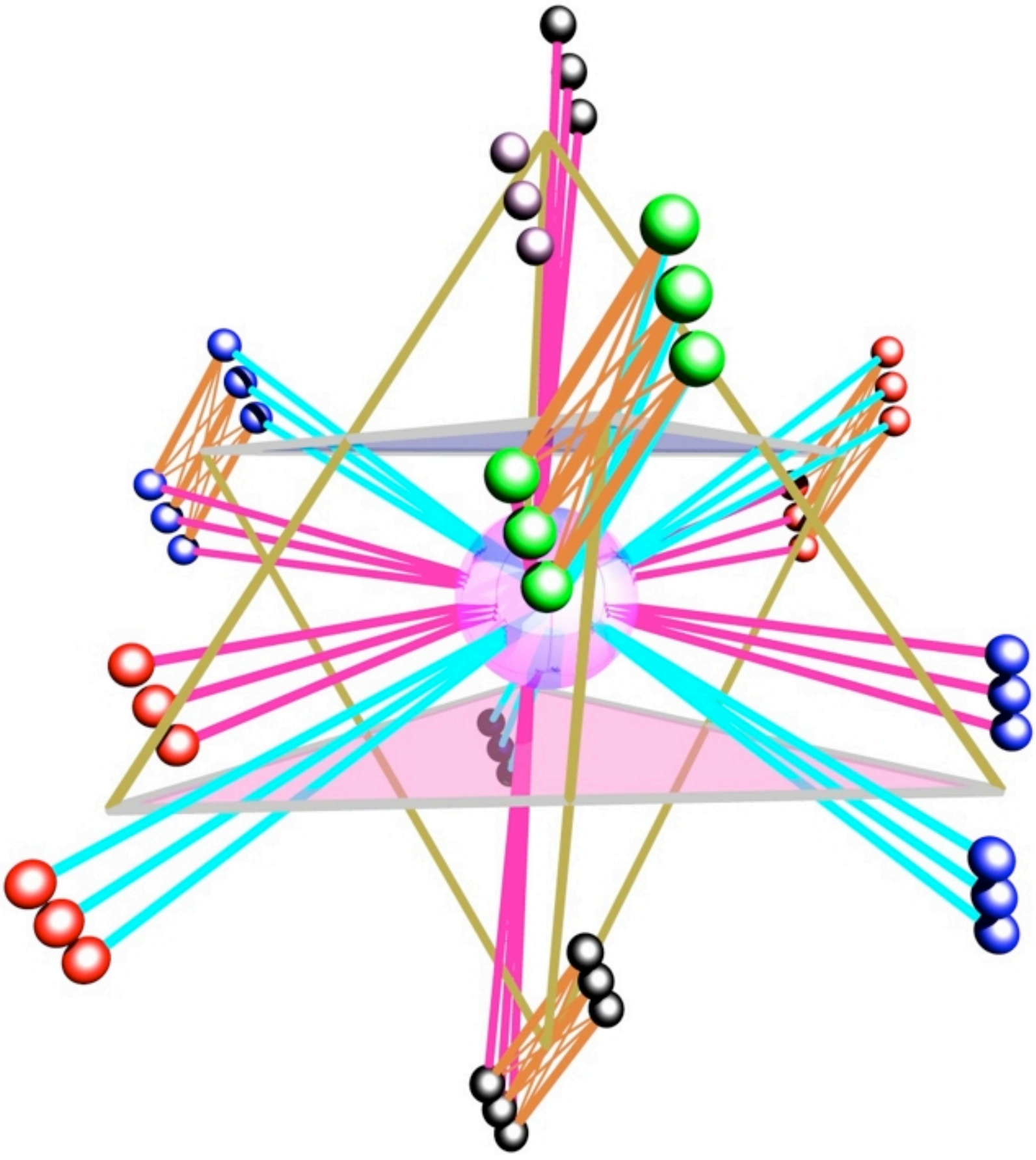

AMERIC VESPVCI
ASIA
VNIVERSALIS COSMOGRAPHIA
SECVNDVM PTHOLOMAEI TRADITIONEM
ET AMERICI VESPVCII ALIORVM

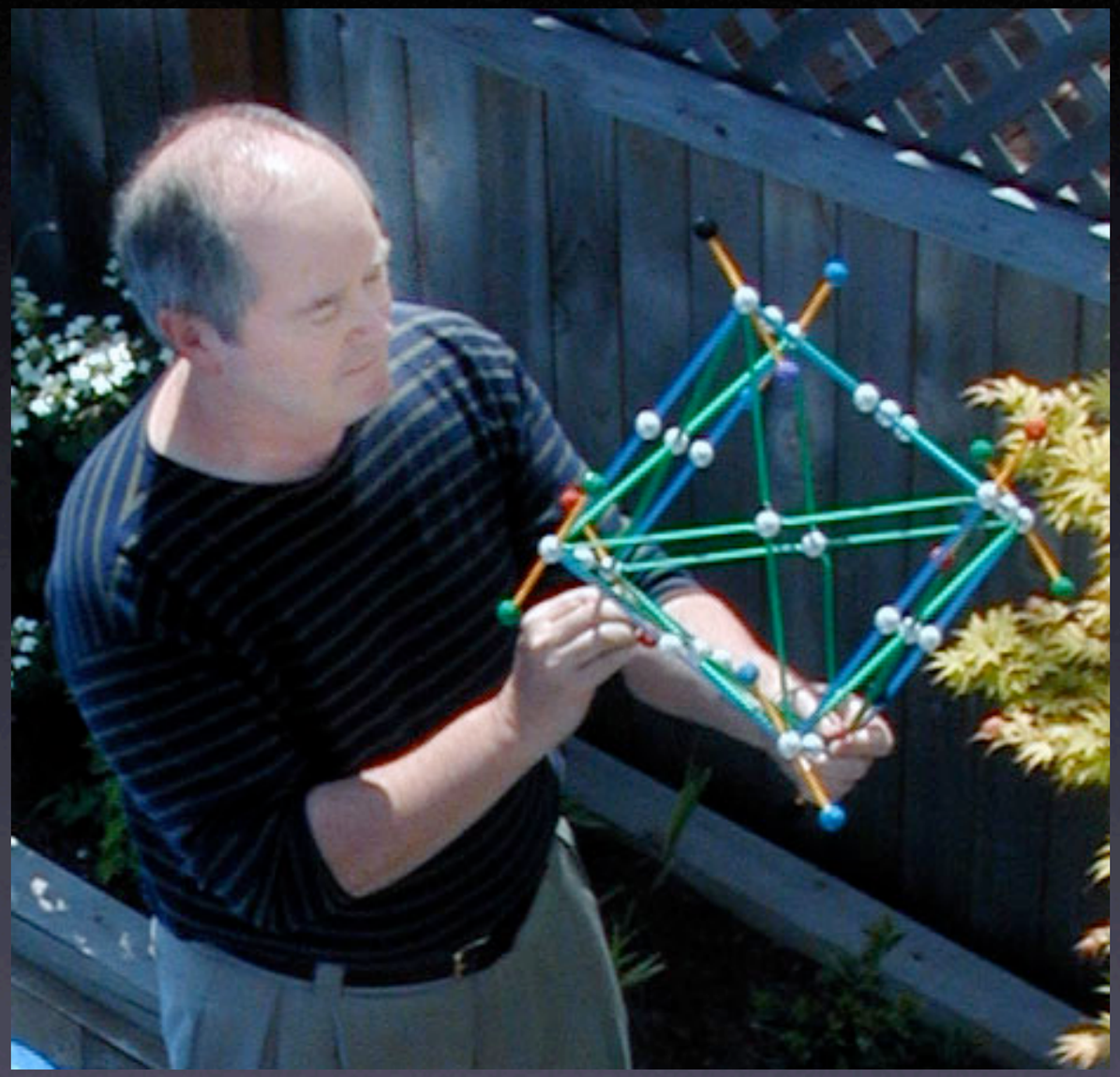


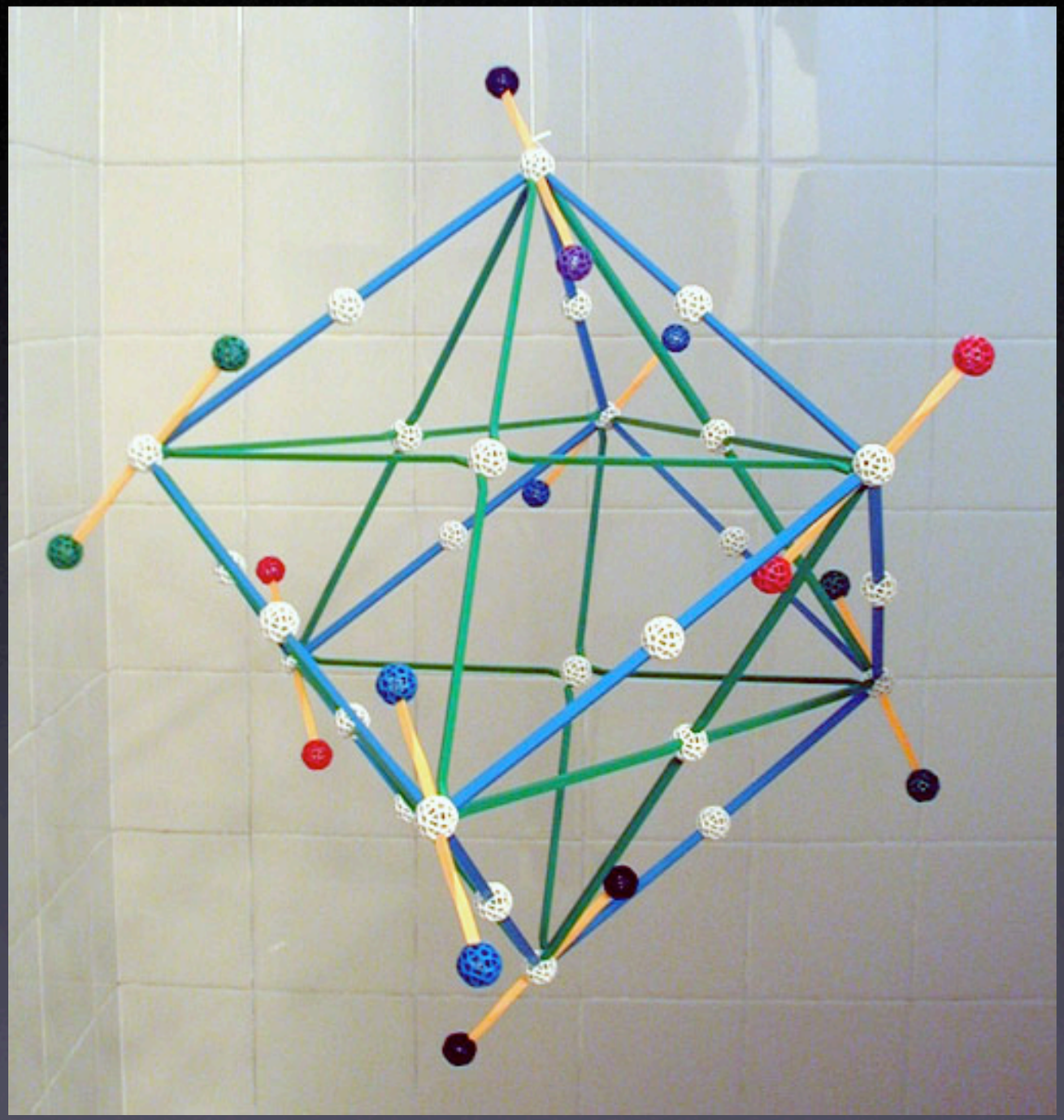
Mendele'ev didn't know about noble gases

Are quarks and leptons elementary?
What relationship of quarks to leptons?
Right-handed weak interactions?
New quarks and leptons?
New interactions linking quarks, leptons?
What relationship of LH & RH particles?
Nature of the right-handed neutrino?
Nature of the mysterious new force that hides electroweak symmetry?

Are there different kinds of matter?
Are there new forces of a novel kind?
What do generations mean? How many?
Which quarks go with which leptons?
Is there a family symmetry?
What makes a top quark a top quark, and an electron an electron?
What is the (grand) unifying symmetry?
What hides it?







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Sketchbook at
http://lutece.fnal.gov/DoubleSimplex/