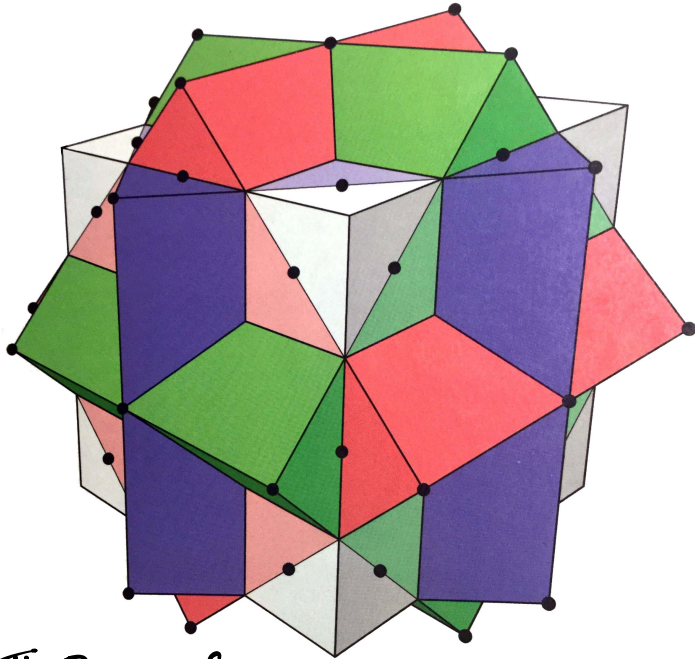


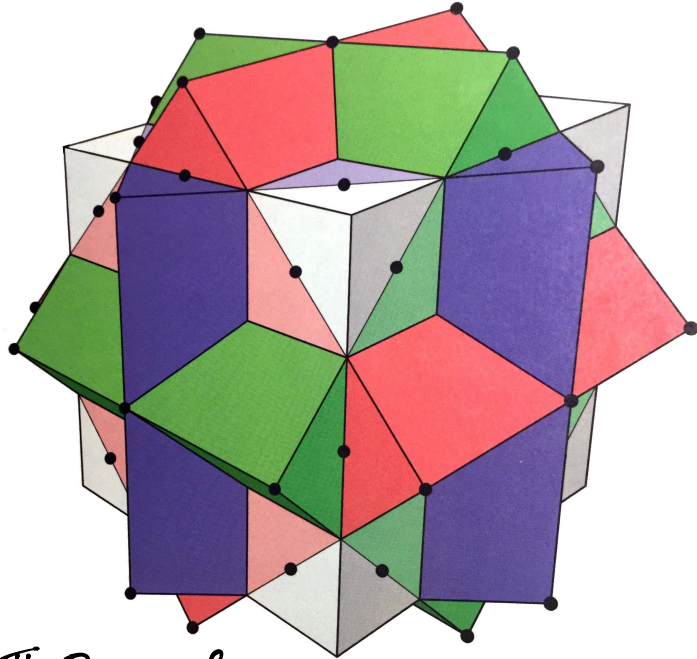
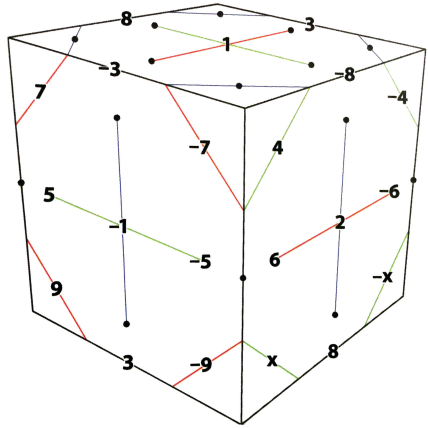
Kochen-Specker Theorem: It is impossible to colour the one-dimensional subspaces of  $\mathbb{R}^3$  red and green, such that every orthogonal frame has exactly one red line.

Kochen-Specker Theorem: It is impossible to colour the one-dimensional subspaces of  $\mathbb{R}^3$  red and green, such that every orthogonal frame has exactly one red line.



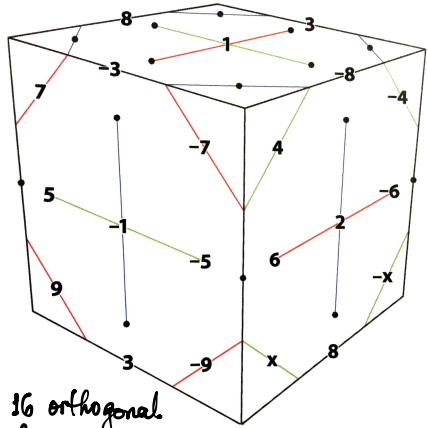
The Peres configuration (33 lines)

**Kochen-Specker Theorem:** It is impossible to colour the one-dimensional subspaces of  $\mathbb{R}^3$  red and green, such that every orthogonal frame has exactly one red line.

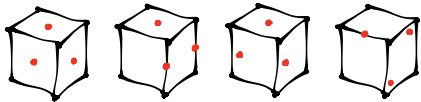


The Peres configuration (33 lines)

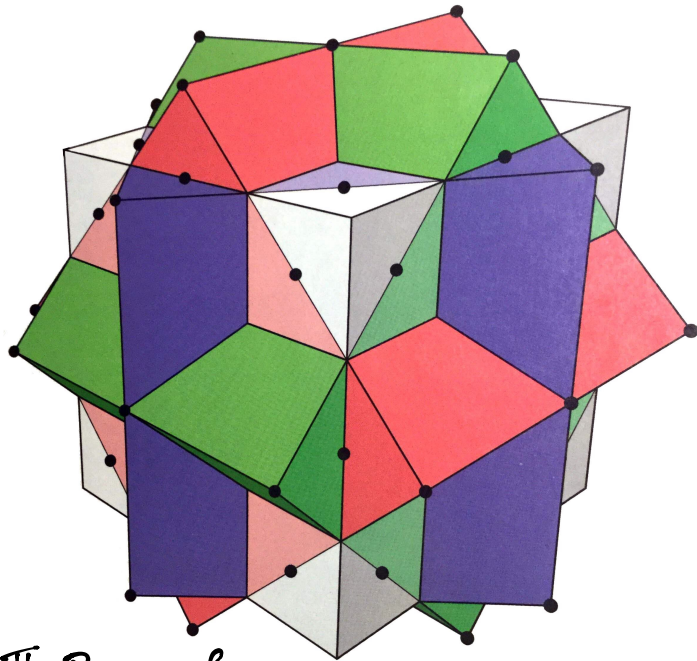
**Kochen-Specker Theorem:** It is impossible to colour the one-dimensional subspaces of  $\mathbb{R}^3$  red and green, such that every orthogonal frame has exactly one red line.



16 orthogonal frames:

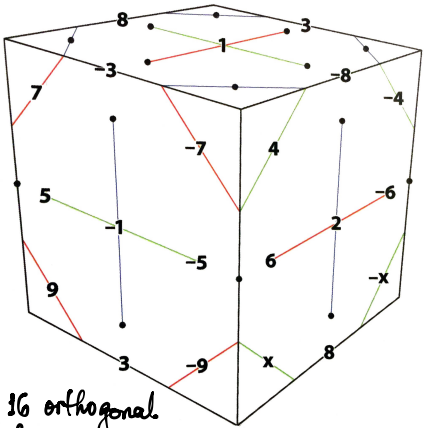


$$1 + 3 + 6 + 6 = 16$$

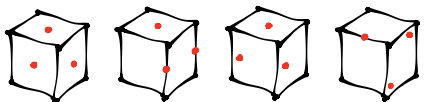


The Peres configuration (33 lines)

**Kochen-Specker Theorem:** It is impossible to colour the one-dimensional subspaces of  $\mathbb{R}^3$  red and green, such that every orthogonal frame has exactly one red line.

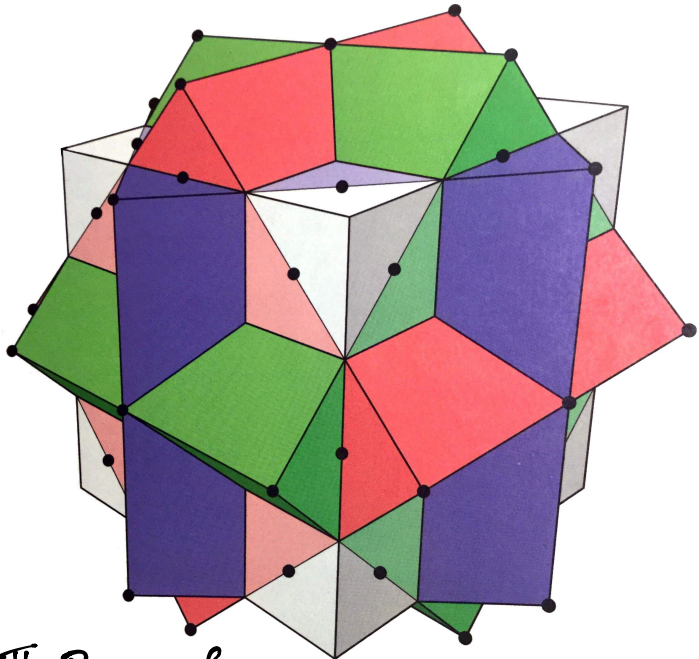
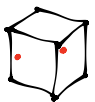


16 orthogonal frames:



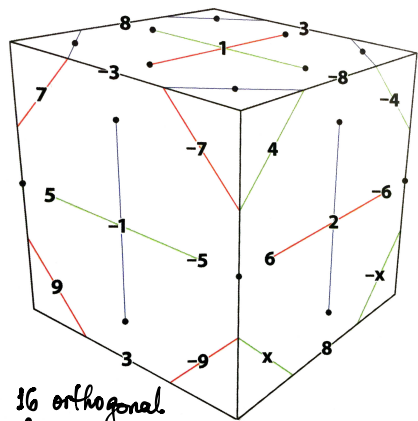
$$1 + 3 + 6 + 6 = 16$$

Another 24 pairs of orthogonal lines:

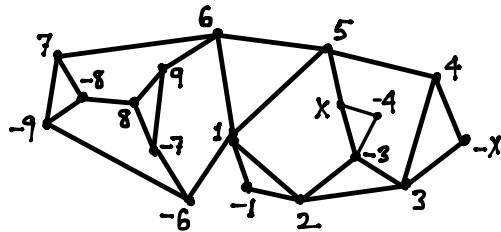


The Peres configuration (33 lines)

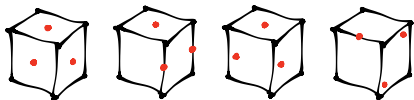
**Koehn-Specker Theorem:** It is impossible to colour the one-dimensional subspaces of  $\mathbb{R}^3$  red and green, such that every orthogonal frame has exactly one red line.



Take the 53 lines as vertices of a graph with edges representing orthogonal pairs. This graph has 16 triangles and 24 further edges. Here is part of the graph:



16 orthogonal frames:

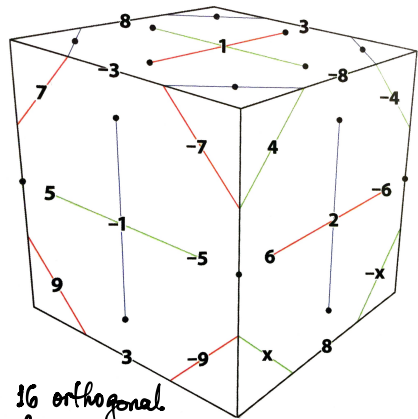


$$1 + 3 + 6 + 6 = 16$$

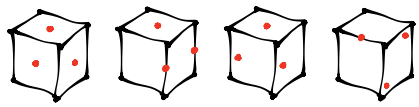
Another 24 pairs of orthogonal lines:



**Kochen-Specker Theorem:** It is impossible to colour the one-dimensional subspaces of  $\mathbb{R}^3$  red and green, such that every orthogonal frame has exactly one red line.

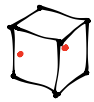


16 orthogonal frames:

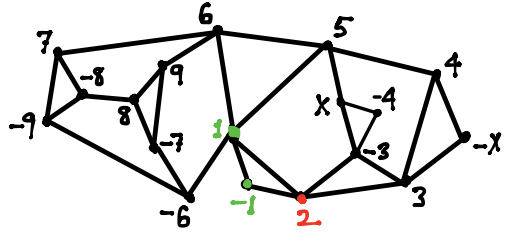


$$1 + 3 + 6 + 6 = 16$$

Another 24 pairs of orthogonal lines:

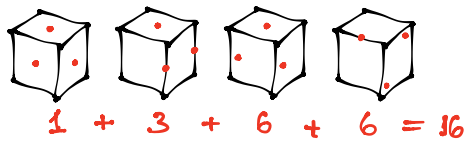
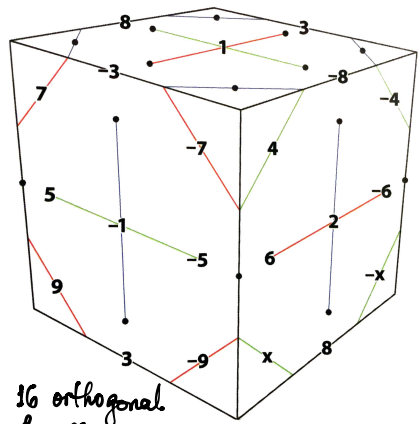


Take the 53 lines as vertices of a graph with edges representing orthogonal pairs. This graph has 16 triangles and 24 further edges. Here is part of the graph:



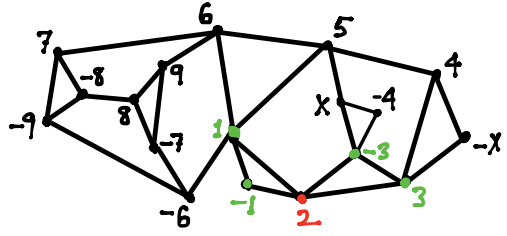
WLOG 1, -1 are green; 2 is red.

**Koehn-Specker Theorem:** It is impossible to colour the one-dimensional subspaces of  $\mathbb{R}^3$  red and green, such that every orthogonal frame has exactly one red line.



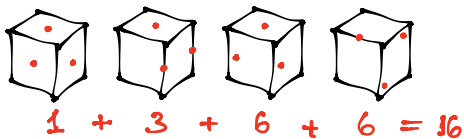
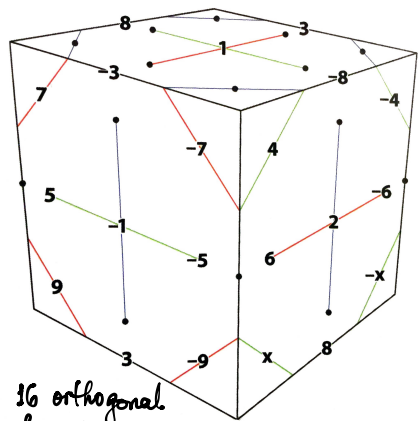
Another 24 pairs of orthogonal lines:

Take the 53 lines as vertices of a graph with edges representing orthogonal pairs. This graph has 16 triangles and 24 further edges. Here is part of the graph:



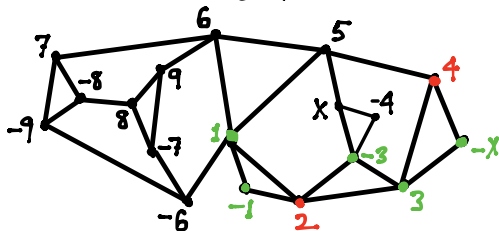
WLOG 1, -1 are green; 2 is red. So 3, -3 are green.

**Kochen-Specker Theorem:** It is impossible to colour the one-dimensional subspaces of  $\mathbb{R}^3$  red and green, such that every orthogonal frame has exactly one red line.



Another 24 pairs of orthogonal lines:

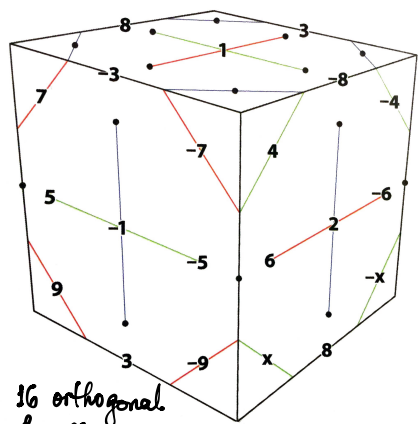
Take the 53 lines as vertices of a graph with edges representing orthogonal pairs. This graph has 16 triangles and 24 further edges. Here is part of the graph:



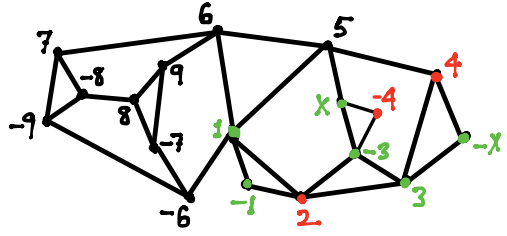
WLOG 1, -1 are green; 2 is red. So 3, -3 are green.

WLOG -x is green. Reflection in  $d_3^\perp = \langle d_1, d_3, d_4, d_x \rangle$  interchanges  $4 \leftrightarrow -x$ ,  $1 \leftrightarrow -1$  while fixing all previously coloured vertices.

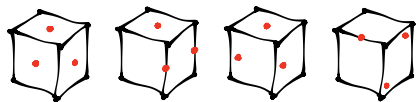
**Kochen-Specker Theorem:** It is impossible to colour the one-dimensional subspaces of  $\mathbb{R}^3$  red and green, such that every orthogonal frame has exactly one red line.



Take the 53 lines as vertices of a graph with edges representing orthogonal pairs. This graph has 16 triangles and 24 further edges. Here is part of the graph:

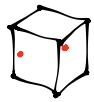


16 orthogonal frames:



$$1 + 3 + 6 + 6 = 16$$

Another 24 pairs of orthogonal lines:

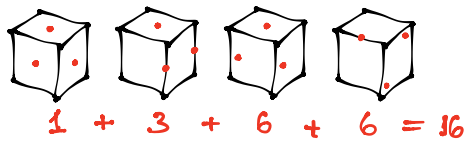
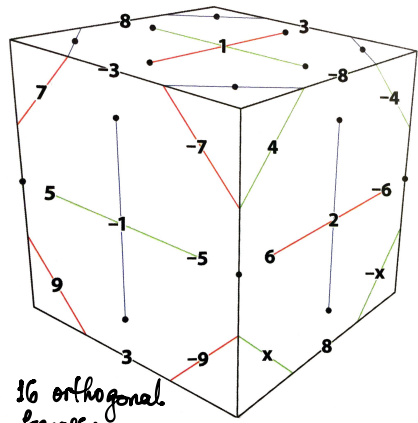


WLOG 1, -1 are green; 2 is red. So 3, -3 are green.

WLOG -X is green. Reflection in  $\mathbb{R}_3^\perp = \langle l_1, l_3, l_4, l_X \rangle$  interchanges  $4 \leftrightarrow -X$ ,  $1 \leftrightarrow -1$  while fixing all previously coloured vertices.

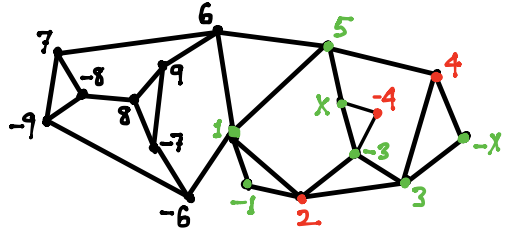
WLOG X is green. Reflection in  $\mathbb{R}_3^\perp = \langle l_2, l_3, l_4, l_X \rangle$  interchanges  $-4 \leftrightarrow X$ ,  $1 \leftrightarrow -1$  while fixing all previously coloured vertices.

**Kochen-Specker Theorem:** It is impossible to colour the one-dimensional subspaces of  $\mathbb{R}^3$  red and green, such that every orthogonal frame has exactly one red line.



Another 24 pairs of orthogonal lines:

Take the 53 lines as vertices of a graph with edges representing orthogonal pairs. This graph has 16 triangles and 24 further edges. Here is part of the graph:

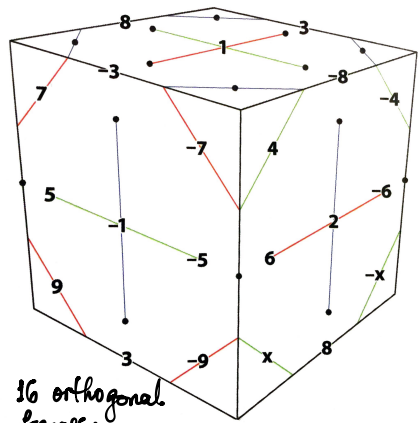


WLOG 1, -1 are green; 2 is red. So 3, -3 are green.

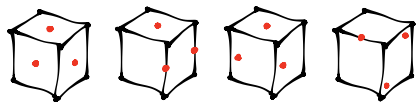
WLOG -X is green. Reflection in  $\mathbb{R}_3^\perp = \langle l_1, l_3, l_4, l_x \rangle$  interchanges  $4 \leftrightarrow -X$ ,  $1 \leftrightarrow -1$  while fixing all previously coloured vertices.

WLOG X is green. Reflection in  $\mathbb{R}_3^\perp = \langle l_2, l_3, l_4, l_x \rangle$  interchanges  $-4 \leftrightarrow X$ ,  $1 \leftrightarrow -1$  while fixing all previously coloured vertices.

**Kochen-Specker Theorem:** It is impossible to colour the one-dimensional subspaces of  $\mathbb{R}^3$  red and green, such that every orthogonal frame has exactly one red line.

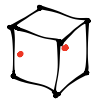


16 orthogonal frames:

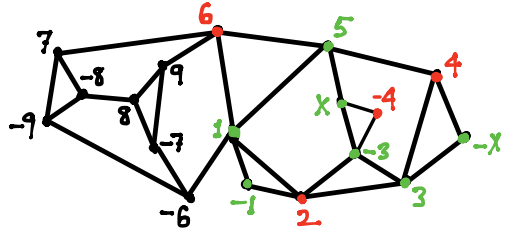


$$1 + 3 + 6 + 6 = 16$$

Another 24 pairs of orthogonal lines:



Take the 53 lines as vertices of a graph with edges representing orthogonal pairs. This graph has 16 triangles and 24 further edges. Here is part of the graph:

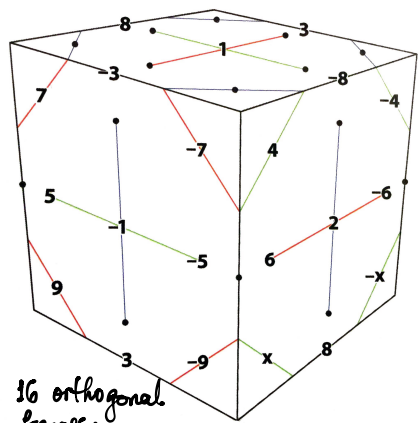


WLOG 1, -1 are green; 2 is red. So 3, -3 are green.

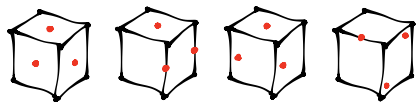
WLOG -X is green. Reflection in  $\mathbb{R}_3^\perp = \langle l_1, l_3, l_4, l_X \rangle$  interchanges  $4 \leftrightarrow -X$ ,  $1 \leftrightarrow -1$  while fixing all previously coloured vertices.

WLOG X is green. Reflection in  $\mathbb{R}_3^\perp = \langle l_2, l_3, l_4, l_X \rangle$  interchanges  $-4 \leftrightarrow X$ ,  $1 \leftrightarrow -1$  while fixing all previously coloured vertices.

**Kochen-Specker Theorem:** It is impossible to colour the one-dimensional subspaces of  $\mathbb{R}^3$  red and green, such that every orthogonal frame has exactly one red line.

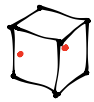


16 orthogonal frames:

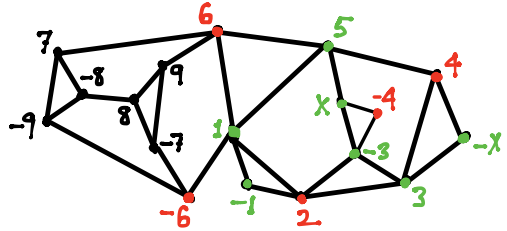


$$1 + 3 + 6 + 6 = 16$$

Another 24 pairs of orthogonal lines:



Take the 53 lines as vertices of a graph with edges representing orthogonal pairs. This graph has 16 triangles and 24 further edges. Here is part of the graph:

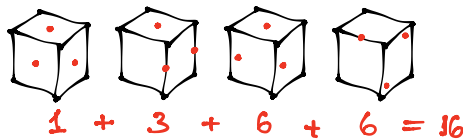
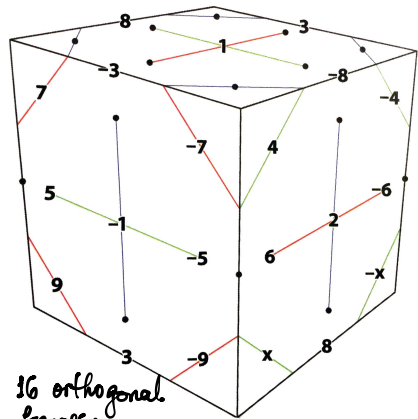



WLOG 1, -1 are green; 2 is red. So 3, -3 are green.

WLOG -X is green. Reflection in  $\mathbb{R}_3^\perp = \langle l_1, l_3, l_4, l_X \rangle$  interchanges  $4 \leftrightarrow -X$ ,  $1 \leftrightarrow -1$  while fixing all previously coloured vertices.

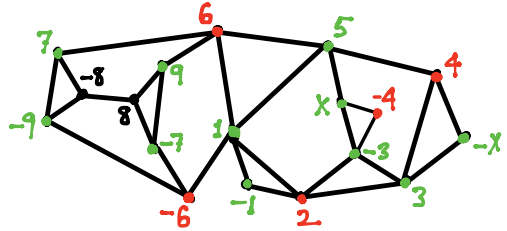
WLOG X is green. Reflection in  $\mathbb{R}_3^\perp = \langle l_2, l_3, l_4, l_X \rangle$  interchanges  $-4 \leftrightarrow X$ ,  $1 \leftrightarrow -1$  while fixing all previously coloured vertices.

**Kochen-Specker Theorem:** It is impossible to colour the one-dimensional subspaces of  $\mathbb{R}^3$  red and green, such that every orthogonal frame has exactly one red line.



Another 24 pairs of orthogonal lines: 

Take the 53 lines as vertices of a graph with edges representing orthogonal pairs. This graph has 16 triangles and 24 further edges. Here is part of the graph:

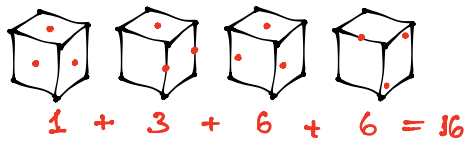
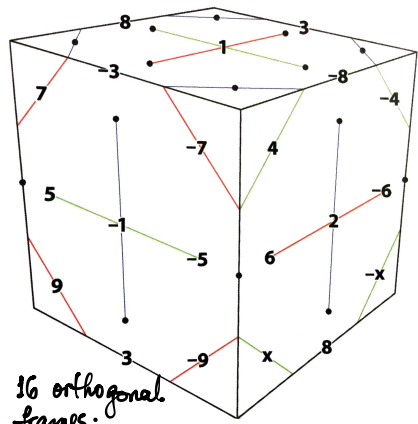


WLOG 1, -1 are green; 2 is red. So 3, -3 are green.

WLOG -X is green. Reflection in  $\mathbb{R}_3^\perp = \langle l_1, l_3, l_4, l_X \rangle$  interchanges  $4 \leftrightarrow -X$ ,  $1 \leftrightarrow -1$  while fixing all previously coloured vertices.

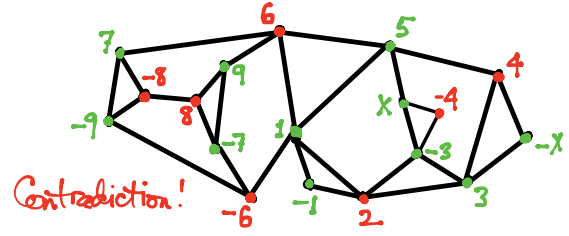
WLOG X is green. Reflection in  $\mathbb{R}_3^\perp = \langle l_2, l_3, l_4, l_X \rangle$  interchanges  $-4 \leftrightarrow X$ ,  $1 \leftrightarrow -1$  while fixing all previously coloured vertices.

**Kochen-Specker Theorem:** It is impossible to colour the one-dimensional subspaces of  $\mathbb{R}^3$  red and green, such that every orthogonal frame has exactly one red line.



Another 24 pairs of orthogonal lines:

Take the 53 lines as vertices of a graph with edges representing orthogonal pairs. This graph has 16 triangles and 24 further edges. Here is part of the graph:



WLOG 1, -1 are green; 2 is red. So 3, -3 are green.

WLOG -X is red. Reflection in  $\mathbb{R}_3^\perp = \langle l_1, l_3, l_4, l_X \rangle$  interchanges  $4 \leftrightarrow -X$ ,  $1 \leftrightarrow -1$  while fixing all previously coloured vertices.

WLOG X is green. Reflection in  $\mathbb{R}_3^\perp = \langle l_2, l_3, l_4, l_X \rangle$  interchanges  $-4 \leftrightarrow X$ ,  $1 \leftrightarrow -1$  while fixing all previously coloured vertices.

***SPIN Axiom.*** *Measurements of the squared (components of) spin of a spin 1 particle in three orthogonal directions always give the answers 1, 0, 1 in some order.*

**SPIN Axiom.** *Measurements of the squared (components of) spin of a spin 1 particle in three orthogonal directions always give the answers 1, 0, 1 in some order.*

**The TWIN Axiom.** *For twinned spin 1 particles, suppose experimenter A performs a triple experiment of measuring the squared spin component of particle a in three orthogonal directions  $x, y, z$ , while experimenter B measures the twinned particle b in one direction,  $w$ . Then, if  $w$  happens to be in the same direction as one of  $x, y, z$ , experimenter B's measurement will necessarily yield the same answer as the corresponding measurement by A.*

**SPIN Axiom.** *Measurements of the squared (components of) spin of a spin 1 particle in three orthogonal directions always give the answers 1, 0, 1 in some order.*

**The TWIN Axiom.** *For twinned spin 1 particles, suppose experimenter A performs a triple experiment of measuring the squared spin component of particle a in three orthogonal directions  $x, y, z$ , while experimenter B measures the twinned particle b in one direction,  $w$ . Then, if  $w$  happens to be in the same direction as one of  $x, y, z$ , experimenter B's measurement will necessarily yield the same answer as the corresponding measurement by A.*

**The MIN Axiom.** *Assume that the experiments performed by A and B are spacelike separated. Then, experimenter B can freely choose any one of the 33 particular directions  $w$ , and a's response is independent of this choice. Similarly and independently, A can freely choose any one of the 40 triples  $x, y, z$ , and b's response is independent of that choice.*

**SPIN Axiom.** *Measurements of the squared (components of) spin of a spin 1 particle in three orthogonal directions always give the answers 1, 0, 1 in some order.*

**The TWIN Axiom.** *For twinned spin 1 particles, suppose experimenter A performs a triple experiment of measuring the squared spin component of particle a in three orthogonal directions  $x, y, z$ , while experimenter B measures the twinned particle b in one direction,  $w$ . Then, if  $w$  happens to be in the same direction as one of  $x, y, z$ , experimenter B's measurement will necessarily yield the same answer as the corresponding measurement by A.*

**The MIN Axiom.** *Assume that the experiments performed by A and B are spacelike separated. Then, experimenter B can freely choose any one of the 33 particular directions  $w$ , and a's response is independent of this choice. Similarly and independently, A can freely choose any one of the 40 triples  $x, y, z$ , and b's response is independent of that choice.*

**The Free Will Theorem.** *The axioms SPIN, TWIN, and MIN imply that the response of a spin 1 particle to a triple experiment is free—that is to say, is not a function of properties of that part of the universe that is earlier than this response with respect to any given inertial frame.*