

# Philosophy of QM 24.111

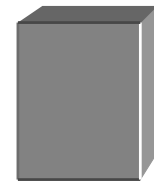
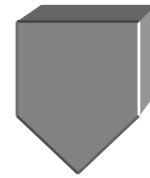
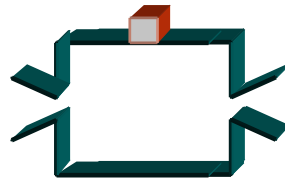
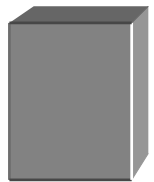
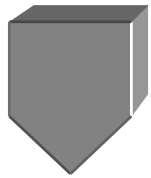
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Ninth lecture,  
28 February, 2005

# Non-locality revisited 1

Spin state of particle pair:

$$\begin{aligned} & \frac{1}{2\sqrt{5}} |\text{up}, 0^\circ\rangle \otimes |\text{down}, 0^\circ\rangle \\ & + \frac{2}{\sqrt{5}} |\text{down}, 0^\circ\rangle \otimes |\text{up}, 0^\circ\rangle \\ & + \frac{\sqrt{3}}{2\sqrt{5}} |\text{down}, 0^\circ\rangle \otimes |\text{down}, 0^\circ\rangle \end{aligned}$$



Left-hand magnet can be set  
to  $0^\circ$  or  $120^\circ$ .

Right-hand magnet can be set  
to  $0^\circ$  or  $-120^\circ$ .

# Non-locality revisited 2

Notice that given this spin state:

$$\begin{aligned} & \frac{1}{2\sqrt{5}} |\text{up}, 0^\circ\rangle \otimes |\text{down}, 0^\circ\rangle \\ & + \frac{2}{\sqrt{5}} |\text{down}, 0^\circ\rangle \otimes |\text{up}, 0^\circ\rangle \\ & + \frac{\sqrt{3}}{2\sqrt{5}} |\text{down}, 0^\circ\rangle \otimes |\text{down}, 0^\circ\rangle \end{aligned}$$

we can conclude that when

**LEFT = 0° and RIGHT = 0°**

The two particles **will never both go up.**

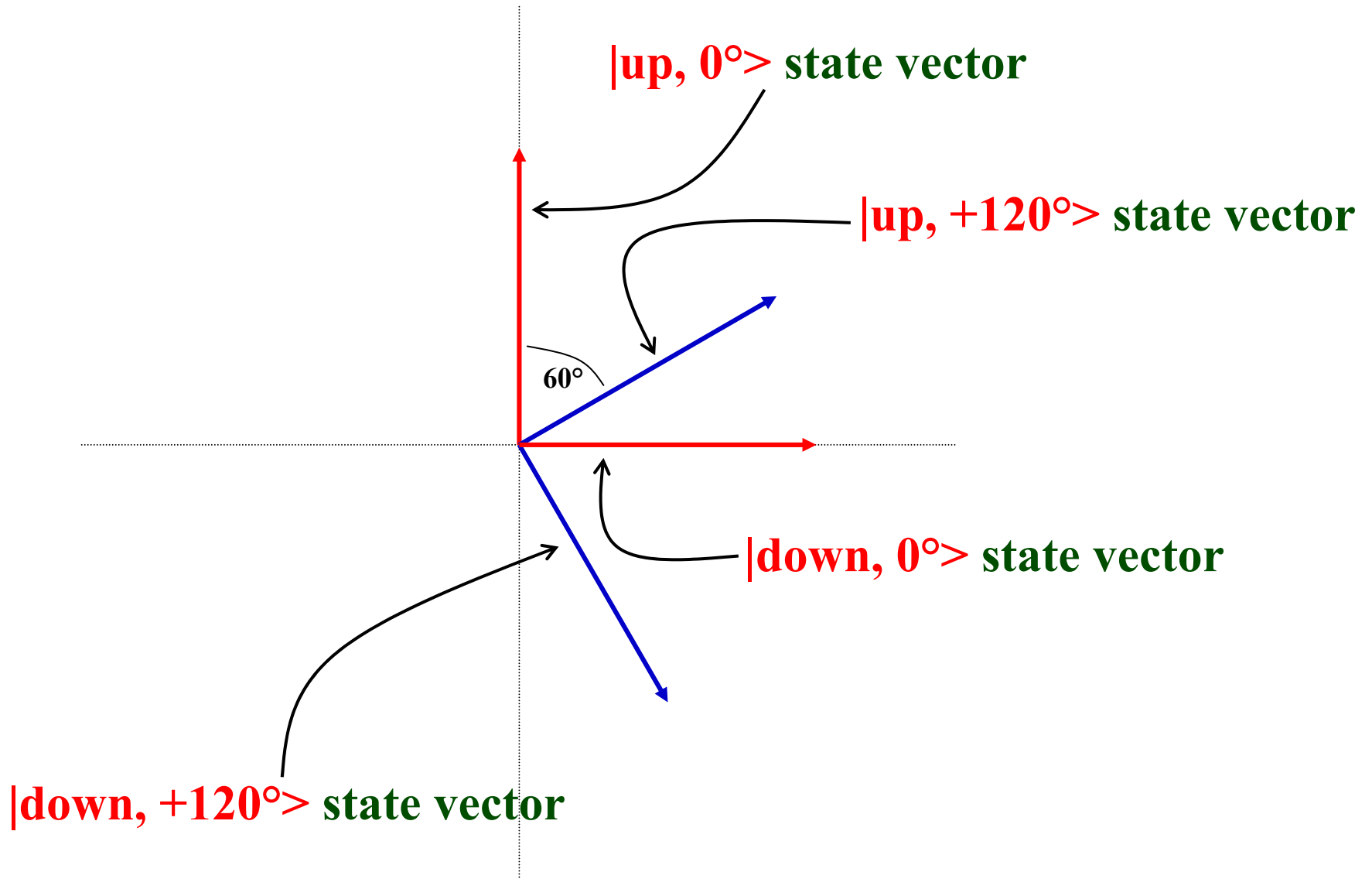
# Non-locality revisited 3

We now rewrite the spin state using the following basis:

$$\left\{ \begin{array}{l} |\text{up}, +120^\circ\rangle \otimes |\text{up}, 0^\circ\rangle, \\ |\text{up}, +120^\circ\rangle \otimes |\text{down}, 0^\circ\rangle, \\ |\text{down}, +120^\circ\rangle \otimes |\text{up}, 0^\circ\rangle, \\ |\text{down}, +120^\circ\rangle \otimes |\text{down}, 0^\circ\rangle \end{array} \right\}$$

To do this, we need to know how to write  $|\text{up}, 0^\circ\rangle$  and  $|\text{down}, 0^\circ\rangle$  as linear combinations of  $|\text{up}, +120^\circ\rangle$  and  $|\text{down}, +120^\circ\rangle$ .

# Non-locality revisited 4

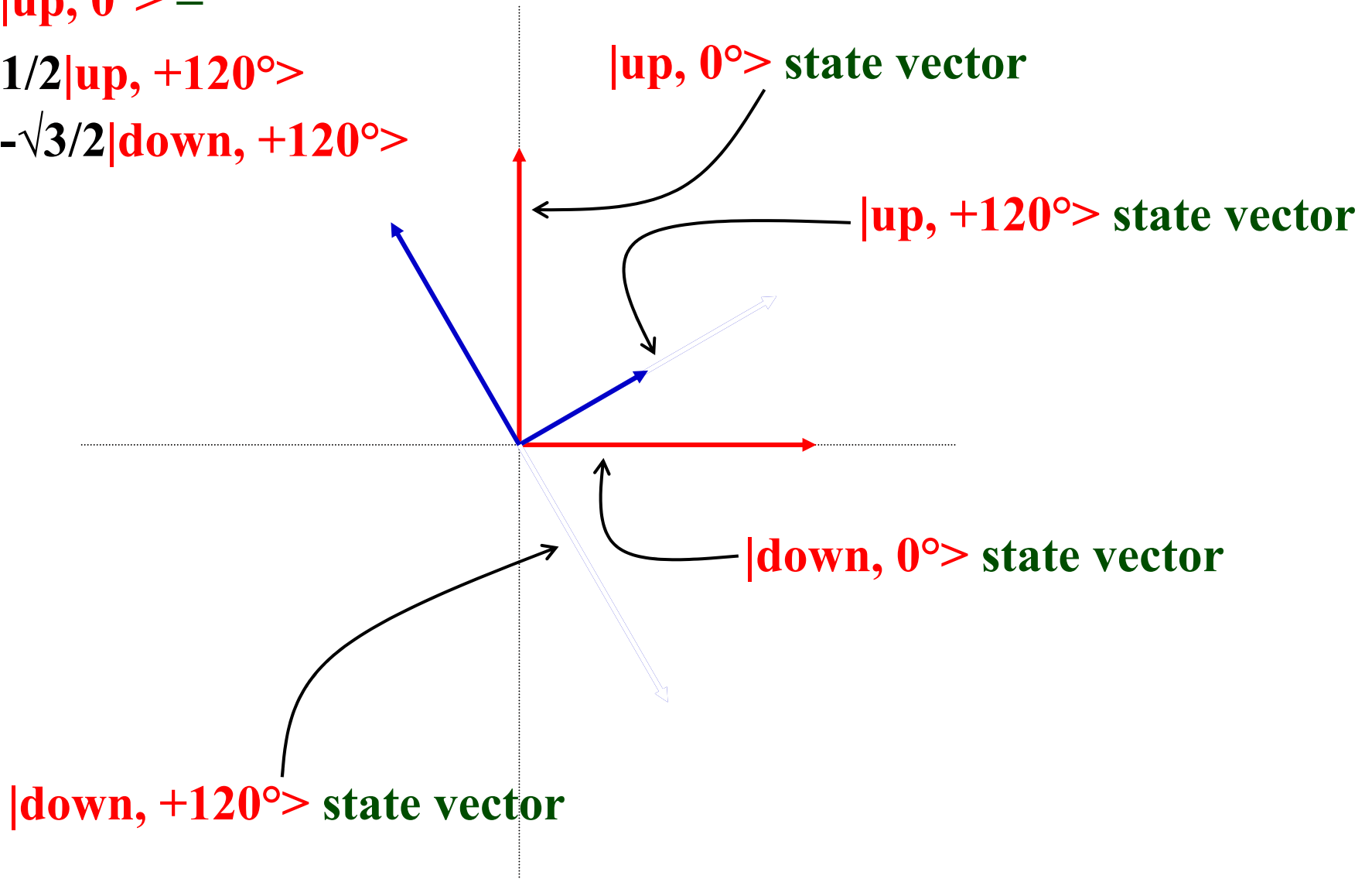


# Non-locality revisited 5

$$|\text{up}, 0^\circ\rangle =$$

$$\frac{1}{2}|\text{up}, +120^\circ\rangle$$

$$-\frac{\sqrt{3}}{2}|\text{down}, +120^\circ\rangle$$

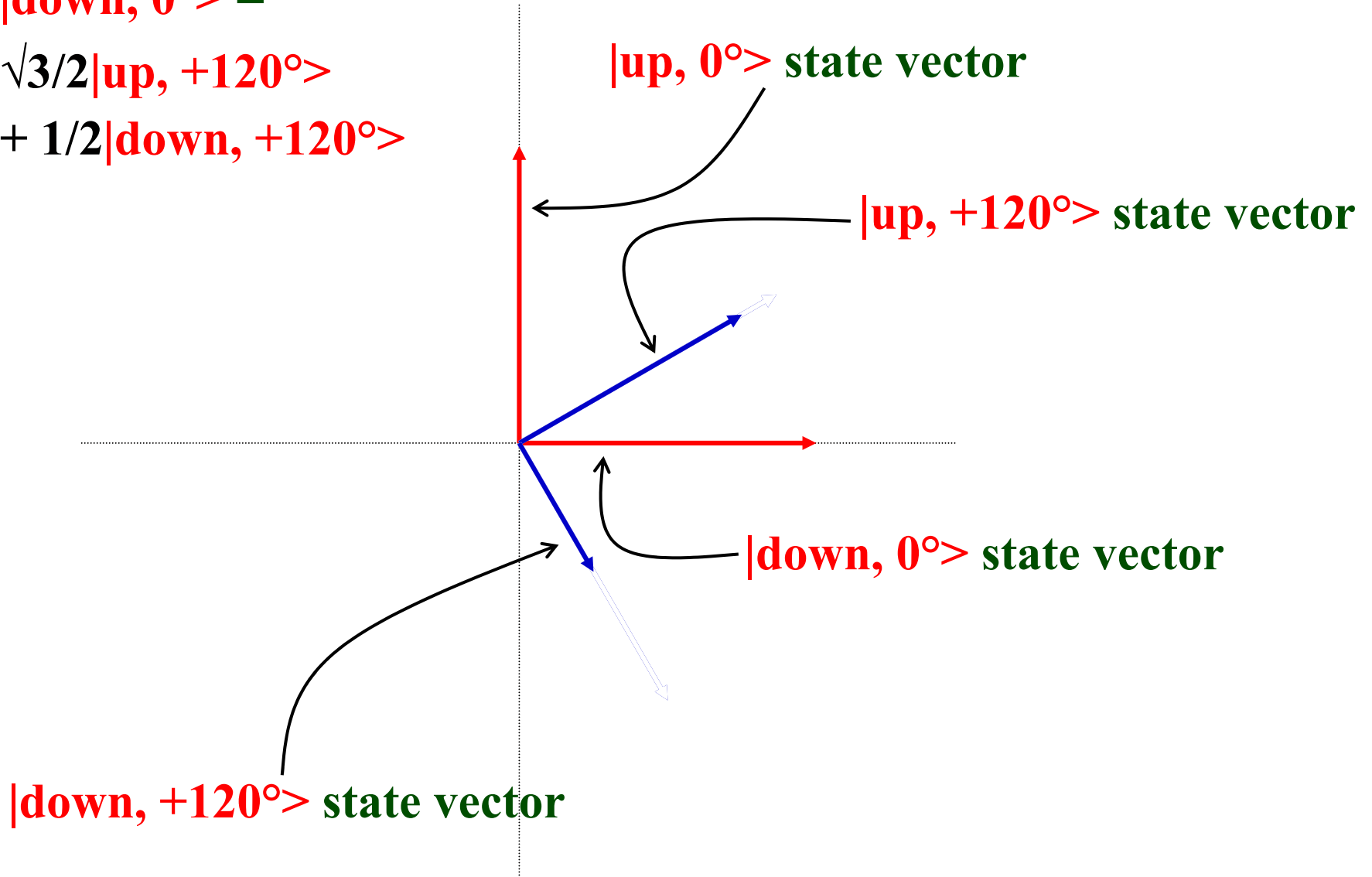


# Non-locality revisited 6

$$|\text{down}, 0^\circ\rangle =$$

$$\sqrt{3/2}|\text{up}, +120^\circ\rangle$$

$$+ 1/2|\text{down}, +120^\circ\rangle$$



# Non-locality revisited 7

$$|\text{up}, 0^\circ\rangle = 1/2 |\text{up}, +120^\circ\rangle - \sqrt{3}/2 |\text{down}, +120^\circ\rangle$$

$$|\text{down}, 0^\circ\rangle = \sqrt{3}/2 |\text{up}, +120^\circ\rangle + 1/2 |\text{down}, +120^\circ\rangle$$

$$1/2\sqrt{5} |\text{up}, 0^\circ\rangle \otimes |\text{down}, 0^\circ\rangle$$

$$1/2\sqrt{5} (1/2 |\text{up}, +120^\circ\rangle - \sqrt{3}/2 |\text{down}, +120^\circ\rangle) \otimes |\text{down}, 0^\circ\rangle$$

$$+ 2/\sqrt{5} |\text{down}, 0^\circ\rangle \otimes |\text{up}, 0^\circ\rangle$$

$$+ 2/\sqrt{5} (\sqrt{3}/2 |\text{up}, +120^\circ\rangle + 1/2 |\text{down}, +120^\circ\rangle) \otimes |\text{up}, 0^\circ\rangle$$

$$+ \sqrt{3}/2\sqrt{5} |\text{down}, 0^\circ\rangle \otimes |\text{down}, 0^\circ\rangle$$

$$+ \sqrt{3}/2\sqrt{5} (\sqrt{3}/2 |\text{up}, +120^\circ\rangle + 1/2 |\text{down}, +120^\circ\rangle) \otimes |\text{down}, 0^\circ\rangle$$



# Non-locality revisited 8

$$\begin{aligned}
 & \frac{1}{2}\sqrt{5} \left( \frac{1}{2} |\text{up}, +120^\circ\rangle - \frac{\sqrt{3}}{2} |\text{down}, +120^\circ\rangle \right) \otimes |\text{down}, 0^\circ\rangle \\
 & + \frac{2}{\sqrt{5}} \left( \frac{\sqrt{3}}{2} |\text{up}, +120^\circ\rangle + \frac{1}{2} |\text{down}, +120^\circ\rangle \right) \otimes |\text{up}, 0^\circ\rangle \\
 & + \frac{\sqrt{3}}{2}\sqrt{5} \left( \frac{\sqrt{3}}{2} |\text{up}, +120^\circ\rangle + \frac{1}{2} |\text{down}, +120^\circ\rangle \right) \otimes |\text{down}, 0^\circ\rangle
 \end{aligned}$$

**Conclusion: when**  
**LEFT = +120°**  
**and**  
**RIGHT = 0°**  
**the particles never**  
**both go down.**

$$\begin{aligned}
 & \frac{\sqrt{3}}{\sqrt{5}} |\text{up}, +120^\circ\rangle \otimes |\text{up}, 0^\circ\rangle \\
 & + \frac{1}{\sqrt{5}} |\text{up}, +120^\circ\rangle \otimes |\text{down}, 0^\circ\rangle \\
 & + \frac{1}{\sqrt{5}} |\text{down}, +120^\circ\rangle \otimes |\text{up}, 0^\circ\rangle \\
 & + 0 |\text{down}, +120^\circ\rangle \otimes |\text{down}, 0^\circ\rangle
 \end{aligned}$$

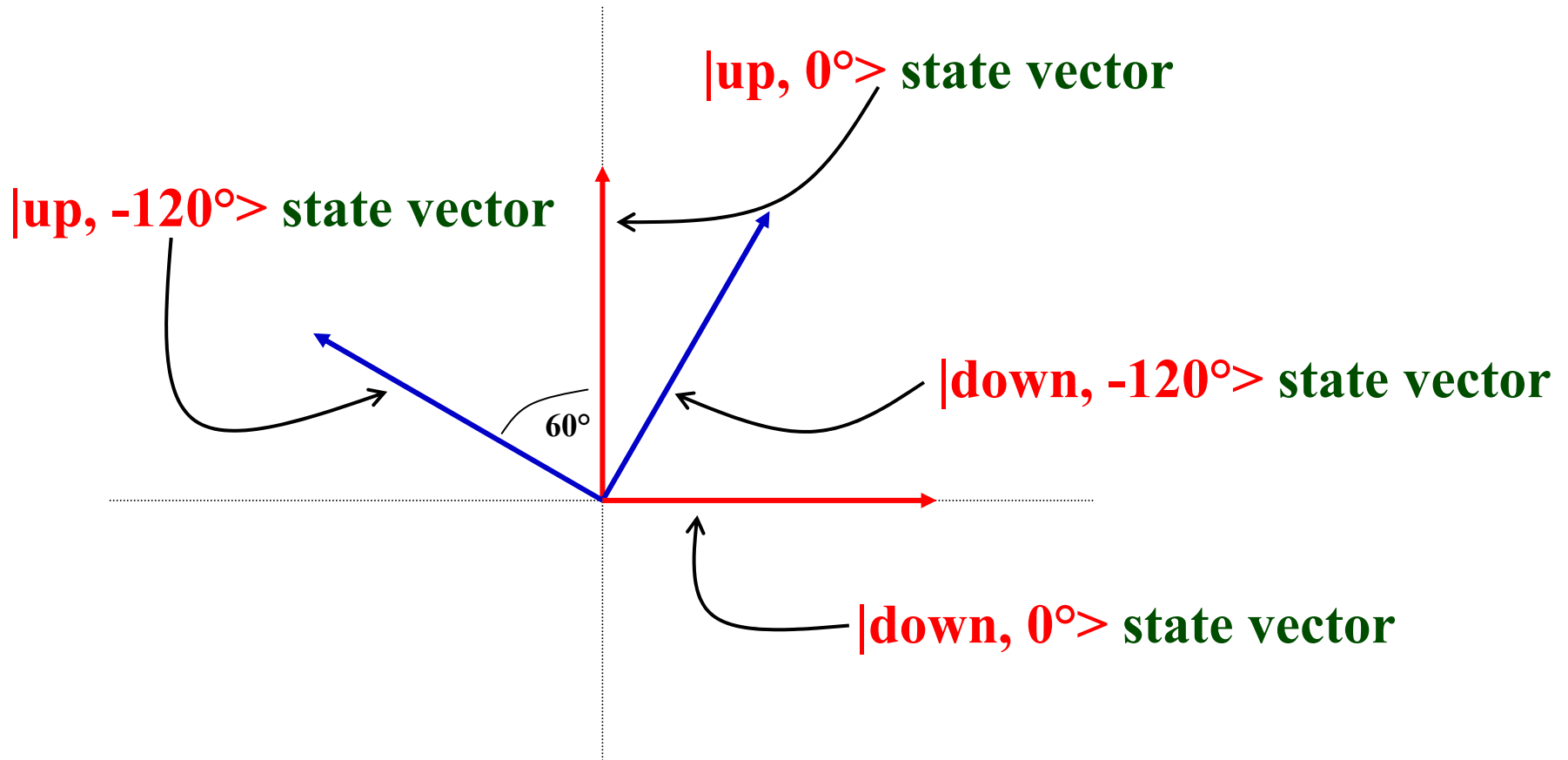
# Non-locality revisited 9

We now rewrite the spin state using the following basis:

$$\left\{ \begin{array}{l} |\text{up}, +120^\circ\rangle \otimes |\text{up}, -120^\circ\rangle, \\ |\text{up}, +120^\circ\rangle \otimes |\text{down}, -120^\circ\rangle, \\ |\text{down}, +120^\circ\rangle \otimes |\text{up}, -120^\circ\rangle, \\ |\text{down}, +120^\circ\rangle \otimes |\text{down}, -120^\circ\rangle \end{array} \right\}$$

To do this, we need to know how to write  $|\text{up}, 0^\circ\rangle$  and  $|\text{down}, 0^\circ\rangle$  as linear combinations of  $|\text{up}, -120^\circ\rangle$  and  $|\text{down}, -120^\circ\rangle$ .

# Non-locality revisited 10



$$|\text{up}, 0^\circ\rangle = \frac{1}{2}|\text{up}, -120^\circ\rangle + \frac{\sqrt{3}}{2}|\text{down}, -120^\circ\rangle$$

$$|\text{down}, 0^\circ\rangle = -\frac{\sqrt{3}}{2}|\text{up}, -120^\circ\rangle + \frac{1}{2}|\text{down}, -120^\circ\rangle$$

# Non-locality revisited 11

$$|\text{up}, 0^\circ\rangle = 1/2 |\text{up}, -120^\circ\rangle + \sqrt{3}/2 |\text{down}, -120^\circ\rangle$$

$$|\text{down}, 0^\circ\rangle = -\sqrt{3}/2 |\text{up}, -120^\circ\rangle + 1/2 |\text{down}, -120^\circ\rangle$$

$$\sqrt{3}/\sqrt{5} |\text{up}, +120^\circ\rangle \otimes |\text{up}, 0^\circ\rangle$$

$$\sqrt{3}/\sqrt{5} |\text{up}, +120^\circ\rangle \otimes (1/2 |\text{up}, -120^\circ\rangle + \sqrt{3}/2 |\text{down}, -120^\circ\rangle)$$

$$+ 1/\sqrt{5} |\text{up}, +120^\circ\rangle \otimes |\text{down}, 0^\circ\rangle$$

$$+ 1/\sqrt{5} |\text{up}, +120^\circ\rangle \otimes (-\sqrt{3}/2 |\text{up}, -120^\circ\rangle + 1/2 |\text{down}, -120^\circ\rangle)$$

$$+ 1/\sqrt{5} |\text{down}, +120^\circ\rangle \otimes |\text{up}, 0^\circ\rangle$$

$$+ 1/\sqrt{5} |\text{down}, +120^\circ\rangle \otimes (1/2 |\text{up}, -120^\circ\rangle + \sqrt{3}/2 |\text{down}, -120^\circ\rangle)$$

# Non-locality revisited 12

$$\begin{aligned} & \sqrt{3}/\sqrt{5} |\text{up}, +120^\circ\rangle \otimes (1/2 |\text{up}, -120^\circ\rangle + \sqrt{3}/2 |\text{down}, -120^\circ\rangle) \\ & + 1/\sqrt{5} |\text{up}, +120^\circ\rangle \otimes (-\sqrt{3}/2 |\text{up}, -120^\circ\rangle + 1/2 |\text{down}, -120^\circ\rangle) \\ & + 1/\sqrt{5} |\text{down}, +120^\circ\rangle \otimes (1/2 |\text{up}, -120^\circ\rangle + \sqrt{3}/2 |\text{down}, -120^\circ\rangle) \end{aligned}$$

**Conclusion:** when  
**LEFT = +120°**  
and  
**RIGHT = -120°**  
the particles never  
both go up.

$$\begin{aligned} & 0 |\text{up}, +120^\circ\rangle \otimes |\text{up}, -120^\circ\rangle \\ & + 2/\sqrt{5} |\text{up}, +120^\circ\rangle \otimes |\text{down}, -120^\circ\rangle \\ & + 1/2\sqrt{5} |\text{down}, +120^\circ\rangle \otimes |\text{up}, -120^\circ\rangle \\ & + \sqrt{3}/2\sqrt{5} |\text{down}, +120^\circ\rangle \otimes |\text{down}, -120^\circ\rangle \end{aligned}$$

# Non-locality revisited 13

$$|\text{up}, 0^\circ\rangle = 1/2 |\text{up}, -120^\circ\rangle + \sqrt{3}/2 |\text{down}, -120^\circ\rangle$$

$$|\text{down}, 0^\circ\rangle = -\sqrt{3}/2 |\text{up}, -120^\circ\rangle + 1/2 |\text{down}, -120^\circ\rangle$$

$$1/2\sqrt{5} |\text{up}, 0^\circ\rangle \otimes |\text{down}, 0^\circ\rangle$$

$$1/2\sqrt{5} |\text{up}, 0^\circ\rangle \otimes (-\sqrt{3}/2 |\text{up}, -120^\circ\rangle + 1/2 |\text{down}, -120^\circ\rangle)$$

$$+ 2/\sqrt{5} |\text{down}, 0^\circ\rangle \otimes |\text{up}, 0^\circ\rangle$$

$$+ 2/\sqrt{5} |\text{down}, 0^\circ\rangle \otimes (1/2 |\text{up}, -120^\circ\rangle + \sqrt{3}/2 |\text{down}, -120^\circ\rangle)$$

$$+ \sqrt{3}/2\sqrt{5} |\text{down}, 0^\circ\rangle \otimes |\text{down}, 0^\circ\rangle$$

$$+ \sqrt{3}/2\sqrt{5} |\text{down}, 0^\circ\rangle \otimes (-\sqrt{3}/2 |\text{up}, -120^\circ\rangle + 1/2 |\text{down}, -120^\circ\rangle)$$

# Non-locality revisited 14

$$\begin{aligned} & \frac{1}{2\sqrt{5}} |\text{up}, 0^\circ\rangle \otimes (-\sqrt{3}/2 |\text{up}, -120^\circ\rangle + 1/2 |\text{down}, -120^\circ\rangle) \\ & + \frac{2}{\sqrt{5}} |\text{down}, 0^\circ\rangle \otimes (1/2 |\text{up}, -120^\circ\rangle + \sqrt{3}/2 |\text{down}, -120^\circ\rangle) \\ & + \frac{\sqrt{3}/2\sqrt{5}}{2} |\text{down}, 0^\circ\rangle \otimes (-\sqrt{3}/2 |\text{up}, -120^\circ\rangle + 1/2 |\text{down}, -120^\circ\rangle) \end{aligned}$$

**Conclusion:** when  
**LEFT = 0°**  
and  
**RIGHT = -120°**  
the particles  
sometimes both go  
up (prob = 3/80).

$$\begin{aligned} & -\sqrt{3}/4\sqrt{5} |\text{up}, 0^\circ\rangle \otimes |\text{up}, -120^\circ\rangle \\ & + 1/4\sqrt{5} |\text{up}, 0^\circ\rangle \otimes |\text{down}, -120^\circ\rangle \\ & + 1/4\sqrt{5} |\text{down}, 0^\circ\rangle \otimes |\text{up}, -120^\circ\rangle \\ & + 5\sqrt{3}/4\sqrt{5} |\text{down}, 0^\circ\rangle \otimes |\text{down}, -120^\circ\rangle \end{aligned}$$

# The basic principles of qm

(1) The physical state of any system is represented by a **vector** in some vector space (usually an **infinite-dimensional** vector space; note that this will be a **different** vector space for each different system).

(2) If  $\Phi$  is a vector representing one possible physical state of some system, and  $\Psi$  is another vector representing another possible physical state of that system, then any arbitrary **linear combination**  $a\Phi + b\Psi$  also represents a possible physical state of the system. This is called the **principle of superposition**.

(3) Any **experiment** that can be performed on a system is represented by an **orthonormal basis** in the vector space for that system. Each basis element can be thought of as “labeled” with one of the possible **outcomes** of the experiment.

We will now amend this principle.





# Subspaces of vector spaces 1

Imagine a 5-dimensional vector space over the reals—think of it as just the set of all 5-tuples of real numbers  $(x_1, x_2, x_3, x_4, x_5)$ .

Here is one such vector  $v_1$ :  $(1, 2, 3, 4, 5)$ .

Here is another such vector  $v_2$ :  $(2, 3, 5, 7, 11)$ .

Here is a linear combination of  $v_1$  and  $v_2$ :

$$\underline{-0.68} \begin{pmatrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{pmatrix} + \underline{1.21} \begin{pmatrix} 2 \\ 3 \\ 5 \\ 7 \\ 11 \end{pmatrix} = \begin{pmatrix} 1.74 \\ 2.27 \\ 4.01 \\ 5.75 \\ 9.91 \end{pmatrix}$$

# Subspaces of vector spaces 2

Imagine a 5-dimensional vector space over the reals—think of it as just the set of all 5-tuples of real numbers  $(x_1, x_2, x_3, x_4, x_5)$ .

Here is one such vector  $v_1$ :  $(1, 2, 3, 4, 5)$ .

Here is another such vector  $v_2$ :  $(2, 3, 5, 7, 11)$ .

Here is another linear combination of  $v_1$  and  $v_2$ :

$$\underline{208} \begin{pmatrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{pmatrix} + \underline{-106} \begin{pmatrix} 2 \\ 3 \\ 5 \\ 7 \\ 11 \end{pmatrix} = \begin{pmatrix} -4 \\ 98 \\ 94 \\ 90 \\ -126 \end{pmatrix}$$

# Subspaces of vector spaces 3

Imagine a 5-dimensional vector space over the reals—think of it as just the set of all 5-tuples of real numbers  $(x_1, x_2, x_3, x_4, x_5)$ .

Here is one such vector  $v_1$ :  $(1, 2, 3, 4, 5)$ .

Here is another such vector  $v_2$ :  $(2, 3, 5, 7, 11)$ .

Here is yet another linear combination of  $v_1$  and  $v_2$ :

$$\frac{106}{1} \begin{pmatrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{pmatrix} + \frac{-55}{1} \begin{pmatrix} 2 \\ 3 \\ 5 \\ 7 \\ 11 \end{pmatrix} = \begin{pmatrix} -4 \\ 47 \\ 43 \\ 39 \\ -75 \end{pmatrix}$$

# Subspaces of vector spaces 4

The set of **all** such linear combinations

is the **subspace** “spanned” by  $\mathbf{v}_1$  and  $\mathbf{v}_2$ .

$$\underline{A} \begin{pmatrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{pmatrix} + \underline{B} \begin{pmatrix} 2 \\ 3 \\ 5 \\ 7 \\ 11 \end{pmatrix} = \begin{pmatrix} A+2B \\ 2A+3B \\ 3A+5B \\ 4A+7B \\ 5A+11B \end{pmatrix}$$

# Subspaces of vector spaces 5

How many dimensions does this subspace have?

That's right: **TWO**.

Observe that it has infinitely many orthonormal bases.

For example, these two vectors are orthogonal:

$$\begin{pmatrix} 2 \\ 3 \\ 5 \\ 7 \\ 11 \end{pmatrix} \cdot \begin{pmatrix} -4 \\ 98 \\ 94 \\ 90 \\ -126 \end{pmatrix} = \begin{array}{r} -8 \\ +294 \\ +470 \\ +630 \\ -1386 \\ \hline 0 \end{array}$$

So we can scale them to get an **orthonormal** basis.

# Subspaces of vector spaces 6

How many dimensions does this subspace have?

That's right: **TWO**.

Observe that it has infinitely many orthonormal bases.

Similarly, these two vectors are orthogonal:

$$\begin{pmatrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{pmatrix} \cdot \begin{pmatrix} -4 \\ 47 \\ 43 \\ 39 \\ -75 \end{pmatrix} = \begin{array}{r} -4 \\ +94 \\ +129 \\ +156 \\ -375 \\ \hline 0 \end{array}$$

So, again, we can scale them to get an **orthonormal** basis.

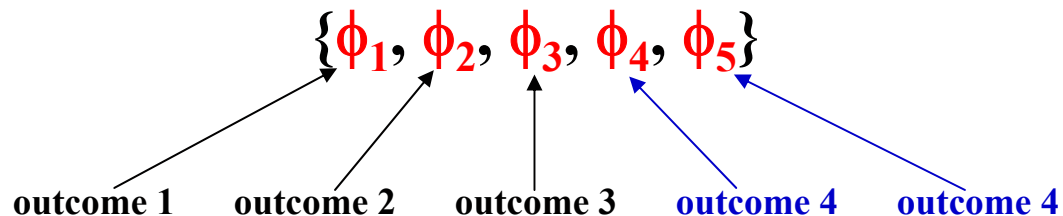
# Degeneracy 1

Suppose the vector space for our system has **five** dimensions.

Suppose the experiment (“measurement”) we are going to perform on it has only **four** possible outcomes.

Still, we represent that experiment by an orthonormal basis—which must have **five elements** in it.

**So: Two of the elements must correspond to the same outcome:**



# Degeneracy 2

Suppose our system is in the state  $\psi$ .

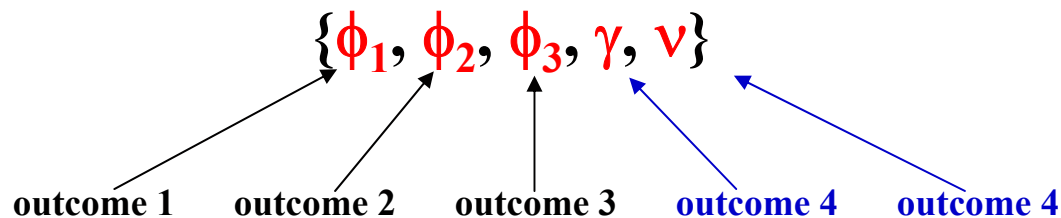
Then the probability that our “measurement” will yield outcome 4 is:

$$|\langle \phi_4 | \psi \rangle|^2 + |\langle \phi_5 | \psi \rangle|^2.$$

Let (normalized, orthogonal) vectors  $\gamma$  and  $\nu$  span the same subspace as  $\phi_4$  and  $\phi_5$ . Then:

$$|\langle \phi_4 | \psi \rangle|^2 + |\langle \phi_5 | \psi \rangle|^2 = |\langle \gamma | \psi \rangle|^2 + |\langle \nu | \psi \rangle|^2 .$$

So we could just as easily have used the following basis to represent our experiment:





# Degeneracy 3

To remove this unwanted redundancy:

Represent outcome 4 **not** by an orthonormal pair of vectors, but rather by the **subspace they span**.

So: An experiment will now be represented by a **set of pairwise-orthogonal subspaces**, each corresponding to a distinct outcome. These subspaces span the entire vector space.

“Pairwise-orthogonal”?

**Explanation:** Subspace  $S_1$  is orthogonal to subspace  $S_2$  iff every vector in  $S_1$  is orthogonal to every vector in  $S_2$ .

# Restating the statistical algorithm

Suppose system **S** is in a state represented by the unit vector  $\Psi$ .

Suppose experiment **E** is performed on **S**, where **E** is represented by the set of pairwise-orthogonal subspaces  $\{S_1, S_2, \dots\}$ , with subspace  $S_i$  corresponding to **outcome i**.

To calculate **Prob(outcome i)**:

1. Project  $\Psi$  onto the subspace  $S_i$ .

This can be done by picking an arbitrary orthonormal basis  $\{\phi_1, \phi_2, \dots\}$  for  $S_i$ , and calculating  $\langle \phi_1 | \Psi \rangle \phi_1 + \langle \phi_2 | \Psi \rangle \phi_2 + \dots$

2. Square the length of the resulting vector.

Given our choice of orthonormal basis  $\{\phi_1, \phi_2, \dots\}$  for  $S_i$ , this will equal  $|\langle \phi_1 | \Psi \rangle|^2 + |\langle \phi_2 | \Psi \rangle|^2 + \dots$

3. The resulting number is **Prob(outcome i)**.

# Hermitian operators 1

An **operator** is simply a function that takes vectors as inputs and yields vectors as outputs:  $\mathbf{A}\Psi = \Phi$ .

A **linear** operator has this additional nice feature:

$$\mathbf{A}(a\Phi + b\Psi) = a\mathbf{A}\Phi + b\mathbf{A}\Psi.$$

A Hermitian operator has yet another nice feature:

$$\langle \mathbf{A}\Phi | \Psi \rangle = \langle \Phi | \mathbf{A}\Psi \rangle.$$

Finally,  $\Phi$  is an eigenvector of  $\mathbf{A}$  iff, for some number  $c$ ,

$$\mathbf{A}\Phi = c\Phi.$$

$c$  is called the **eigenvalue** of  $\Phi$  (for  $\mathbf{A}$ ). Note that  $\mathbf{A}$  will have some **set** of eigenvalues.

# Hermitian operators 2

Some cool results:

1. If  $\Phi$  and  $\Psi$  are eigenvectors of (linear) operator  $\mathbf{A}$ , with the same eigenvalue  $\mathbf{c}$ , then so is  $(a\Phi + b\Psi)$ .

That means that for each eigenvalue  $\mathbf{c}$  of  $\mathbf{A}$ , there is a **subspace** consisting of all and only those vectors with eigenvalue  $\mathbf{c}$  for  $\mathbf{A}$ . We call these subspace **eigenspaces** for  $\mathbf{A}$ .

2. If  $\Phi$  and  $\Psi$  are eigenvectors of **Hermitian** operator  $\mathbf{A}$ , with **different** eigenvalues, then  $\Phi$  and  $\Psi$  are **orthogonal**.

That means that for a Hermitian operator  $\mathbf{A}$ , its eigenspaces are **pairwise-orthogonal**.

So a Hermitian operator automatically “picks out” a set of pairwise-orthogonal subspaces, each labeled with a distinct eigenvalue. That makes these operators **particularly well suited to represent experiments**.

# Hermitian operators 3

Haven't we forgotten something? After all, we can also show:

3. If  $\Phi$  is an eigenvector of Hermitian operator  $A$ , then the eigenvalue  $c$  is a real number.

Supposedly this is a **BIG DEAL**, since “only real numbers could be the values of some measured physical quantity”.

**Exercise:** Explain why this claim is—**notwithstanding its prominent position in just about every quantum mechanics textbook—COMPLETE AND UTTER NONSENSE.**

# Two measurement problems 1

**Schrödinger's Equation:** the state of the world evolves, at all times, in accordance with Schrödinger's Equation.

Okay, okay: "observable".

**Von Neumann's Rule:** A system **S** has value **v** for physical quantity **Q** iff **S** is in an eigenstate with eigenvalue **v** of the Hermitian operator **A** that represents **Q**.

Okay, okay: "measurement".

**Born's Rule:** If a **Q**-experiment is performed on system **S** in state  $\Psi$ , then the expected value of the outcome is  $\langle \Psi | A \Psi \rangle$ . (This turns out to be equivalent to our statistical algorithm.)

# Two measurement problems 2

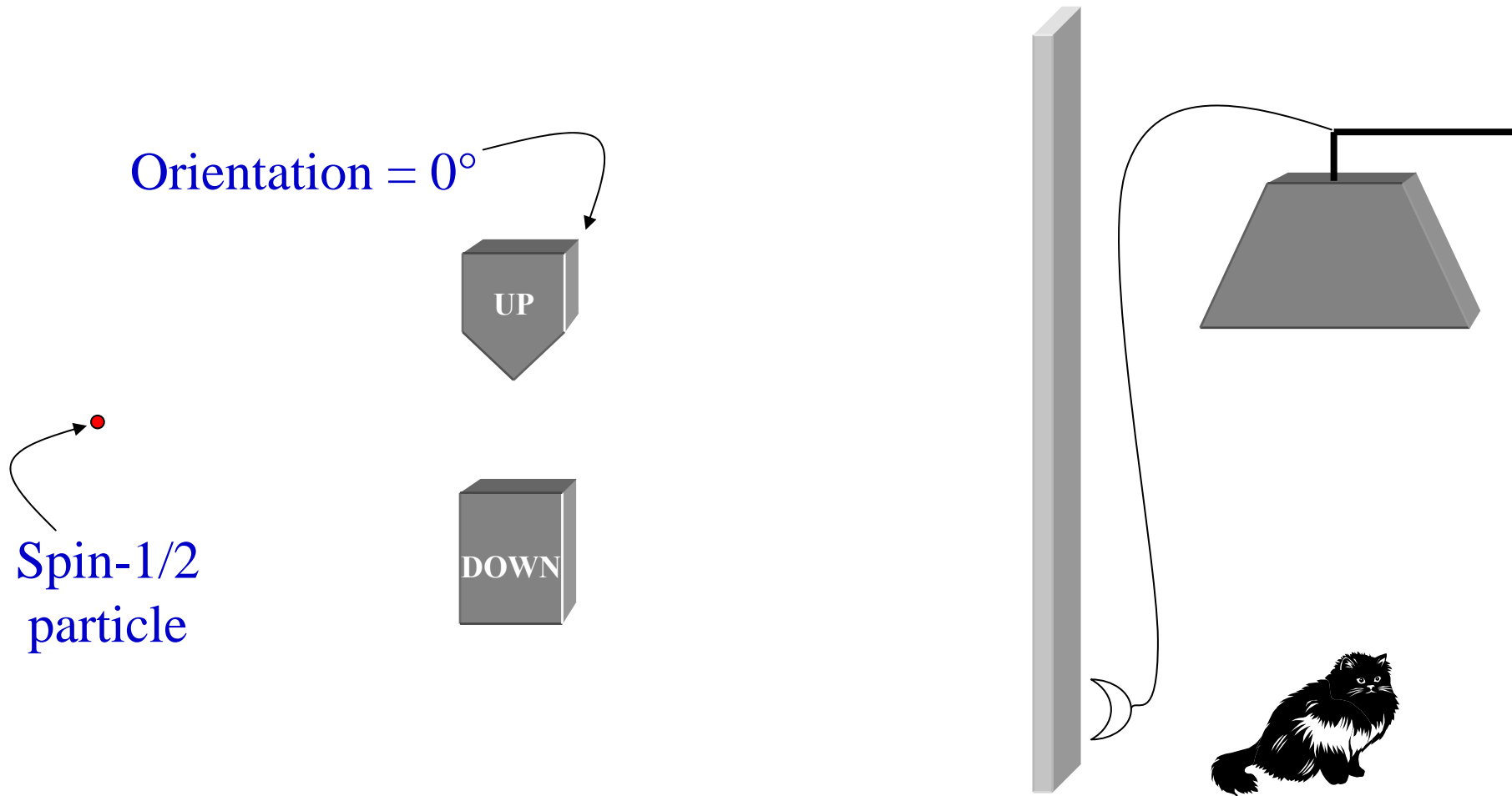
Schrödinger's Equation + von Neumann's Rule gives us one problem:

**Systems will sometimes possess no value for any recognizable physical quantity.**

Schrödinger's Equation + Born's Rule gives us another:

**CONTRADICTION**

# Illustration: Schrödinger's Cat



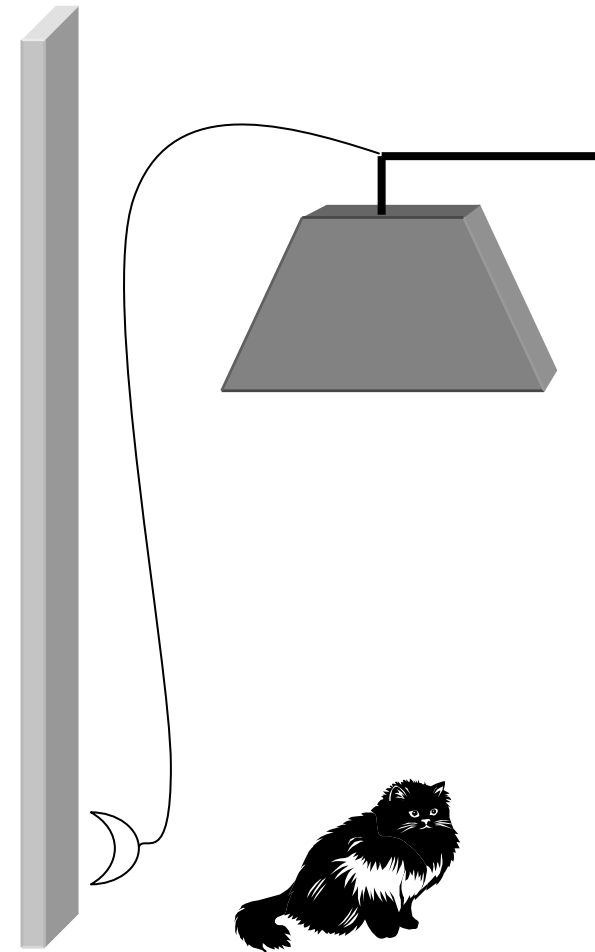


# The nice case

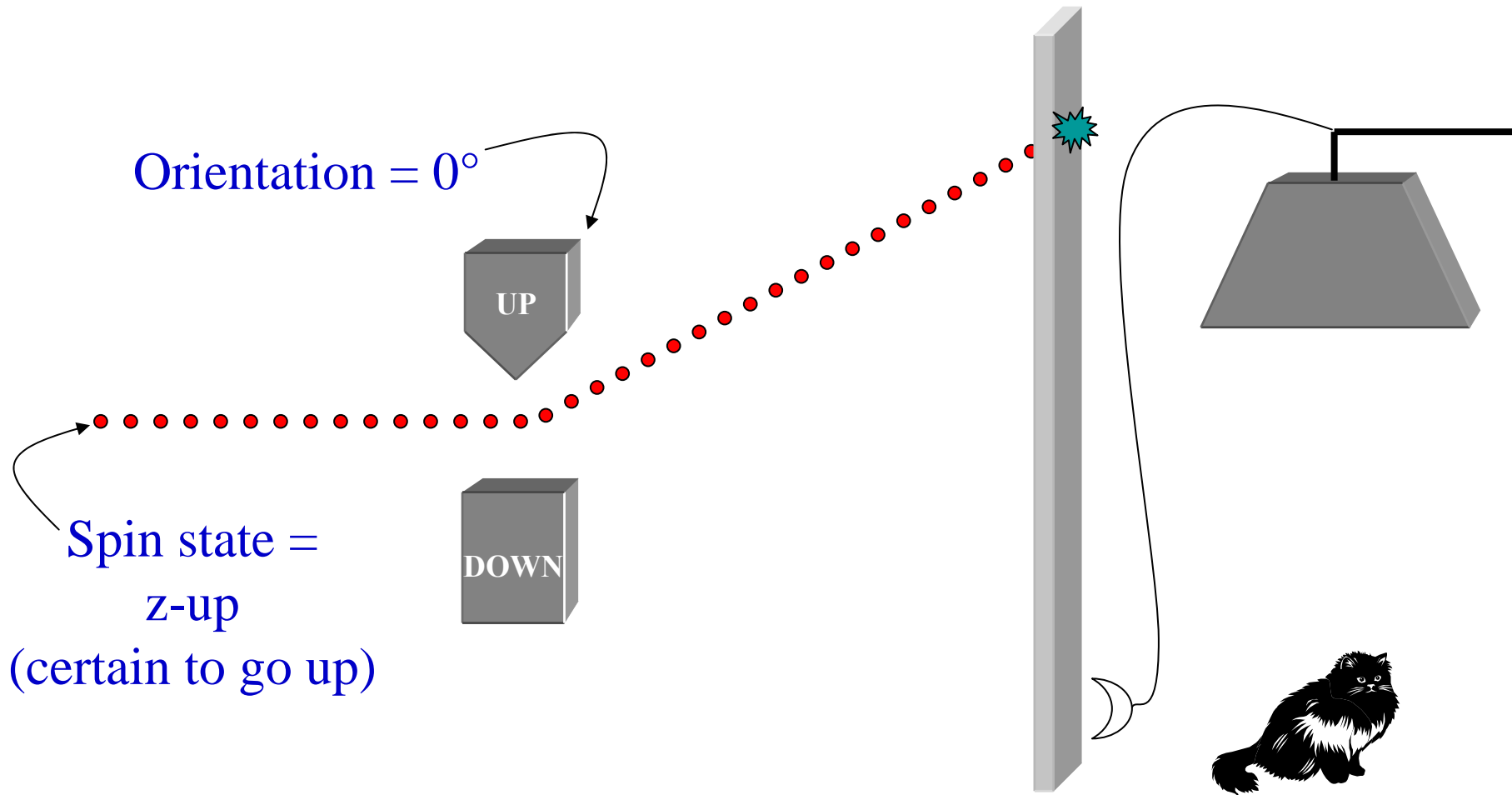
Orientation =  $0^\circ$



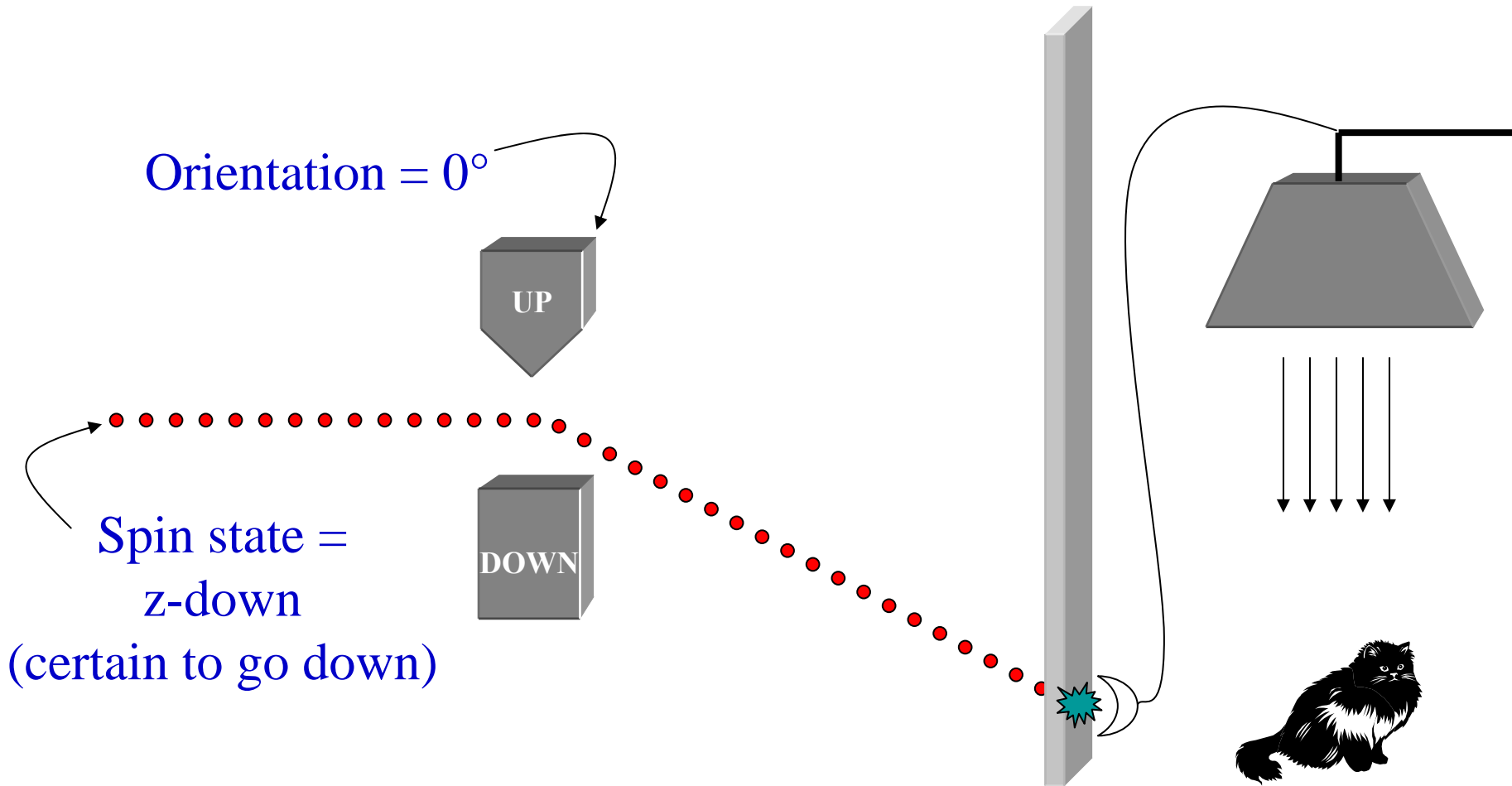
Spin state =  
z-up  
(certain to go up)



# The nice case



# The not-so-nice case

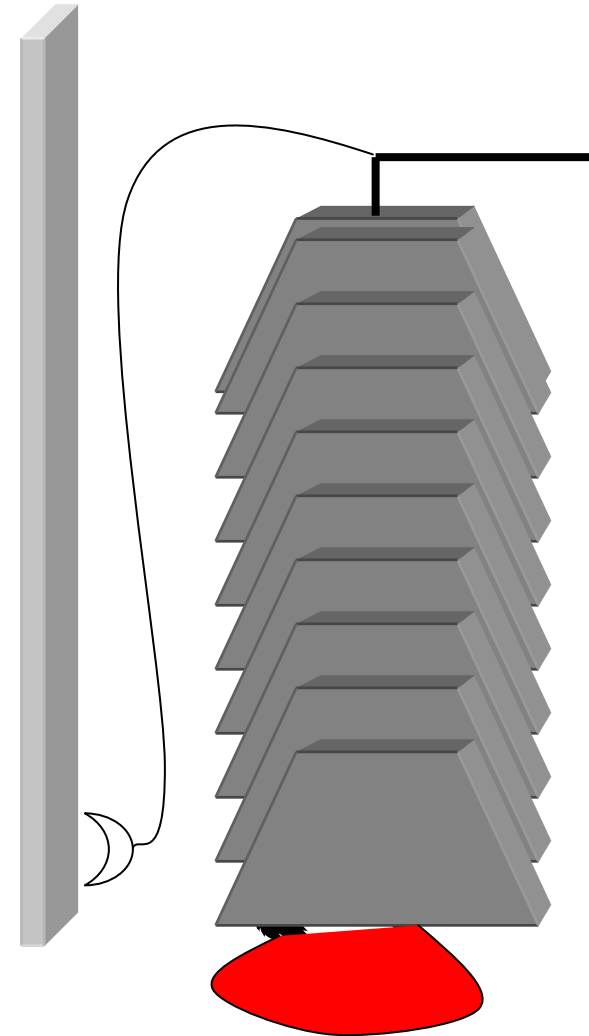


# The not-so-nice case

Orientation =  $0^\circ$



Spin state =  
z-down  
(certain to go down)



# The problem

Nice case: final quantum mechanical state will be

$$|z\text{-up}\rangle | \text{no flash detected}\rangle | \text{block suspended}\rangle | \text{Fluffy purring}\rangle$$

Not-so-nice case: final quantum mechanical state will be

$$|z\text{-down}\rangle | \text{flash detected}\rangle | \text{block has fallen}\rangle | \text{Fluffy squished}\rangle$$

So, if the initial spin state is

$$|x\text{-up}\rangle = 1/\sqrt{2}(|z\text{-up}\rangle + |z\text{-down}\rangle)$$

Then the final quantum mechanical state will be

$$1/\sqrt{2}(|z\text{-up}\rangle | \text{no flash detected}\rangle | \text{block suspended}\rangle | \text{Fluffy purring}\rangle + |z\text{-down}\rangle | \text{flash detected}\rangle | \text{block has fallen}\rangle | \text{Fluffy squished}\rangle).$$

WHAT KIND OF STATE IS THAT?!?

AND WHERE ARE OUR TWO POSSIBLE OUTCOMES?

# The standard menu of options

## 1. Add extra variables.

- Bohmian mechanics, modal interpretations, some versions of Many Minds

## 2. Add non-linear, stochastic dynamics.

- textbook “collapse” theories, GRW

## 3. Give up on Born’s Rule without admitting it.

- Many Worlds, other versions of Many Minds

## 4. Go soft in the head.

- decoherence, the “bare theory”