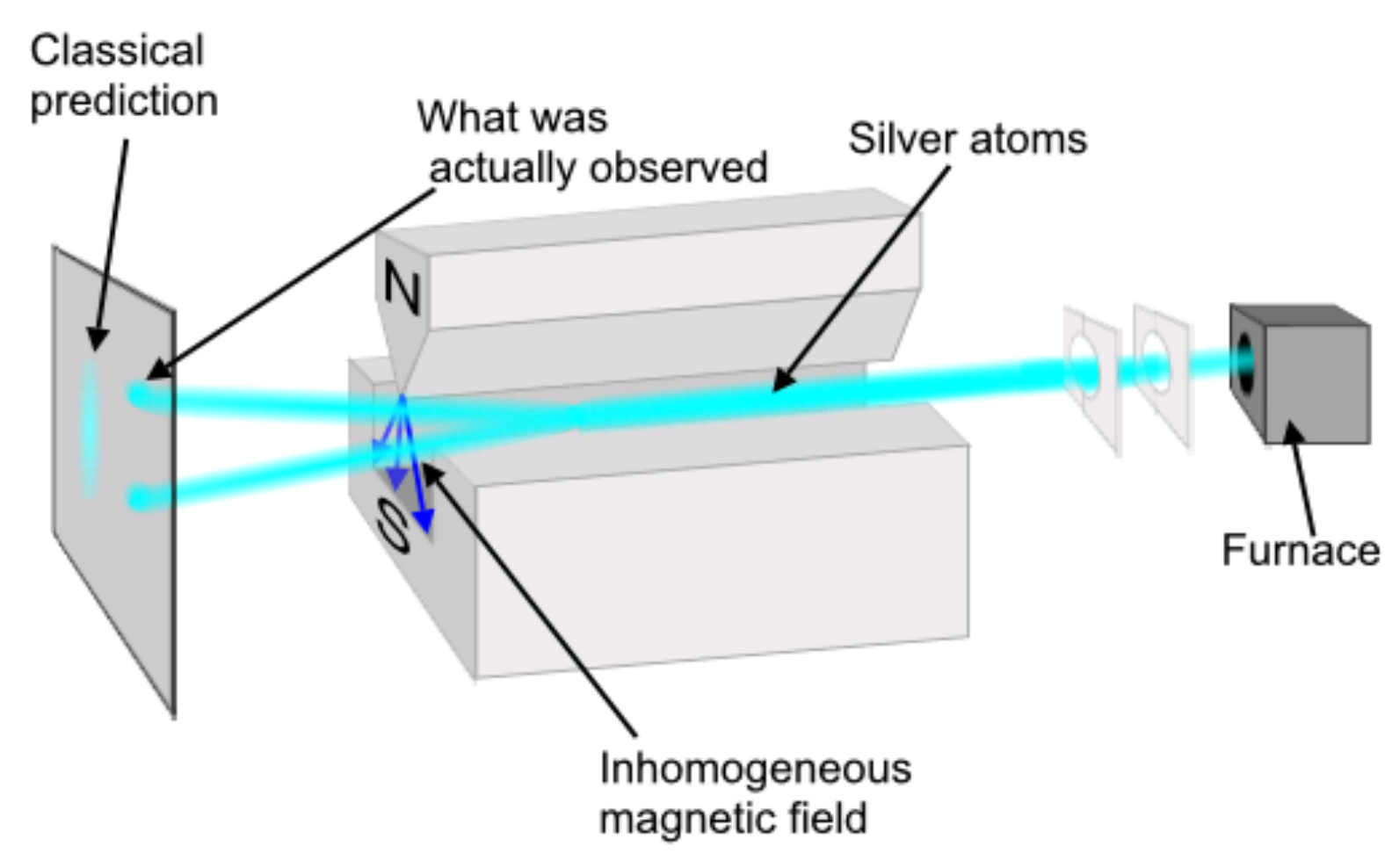
Quantum Mechanics: Interpretation and Philosophy

Significant content from: "Quantum Mechanics and Experience" by David Z. Albert, Harvard University Press (1992).

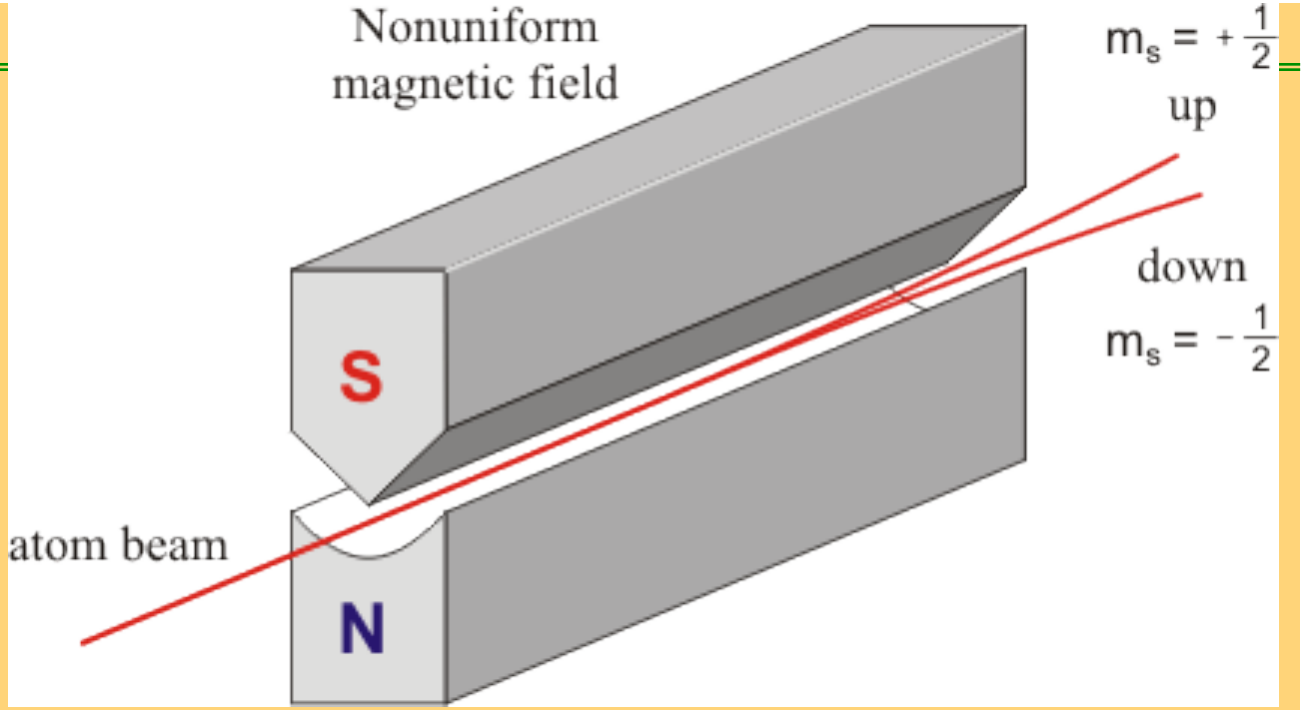
Main Concepts:

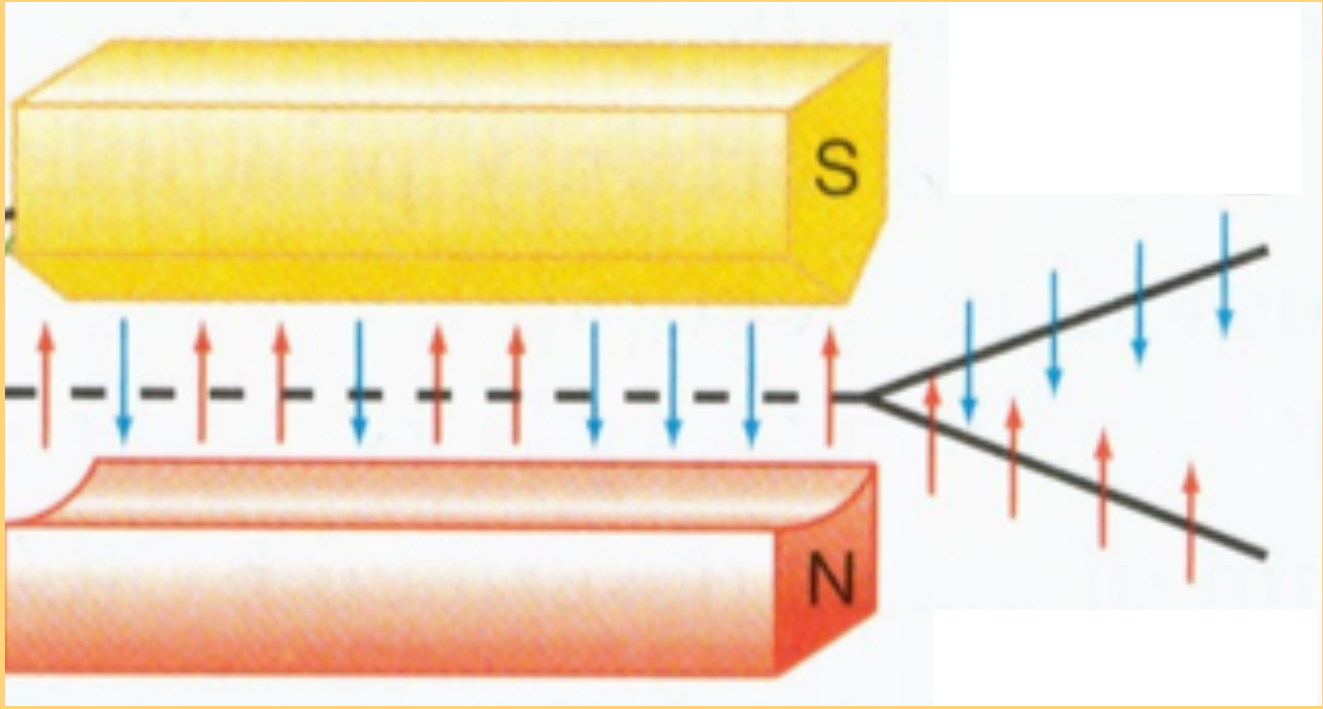
-- complementarity
-- the uncertainty principle
-- superposition
-- collapse of the wavefunction
-- the measurement problem

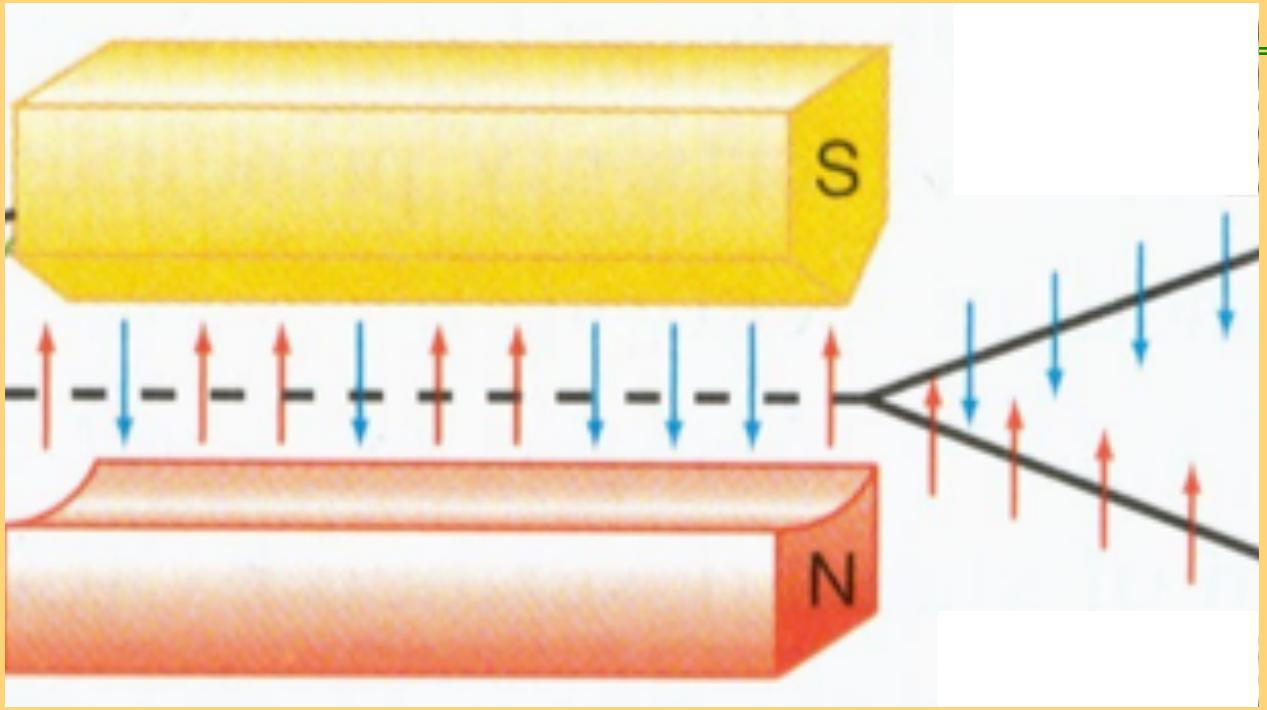
Quantum Mechanics:
The Stern-Gerlach Experiment (1921)



a silver atom has an unpaired electron
(and a charged particle is deflected by a magnetic field)

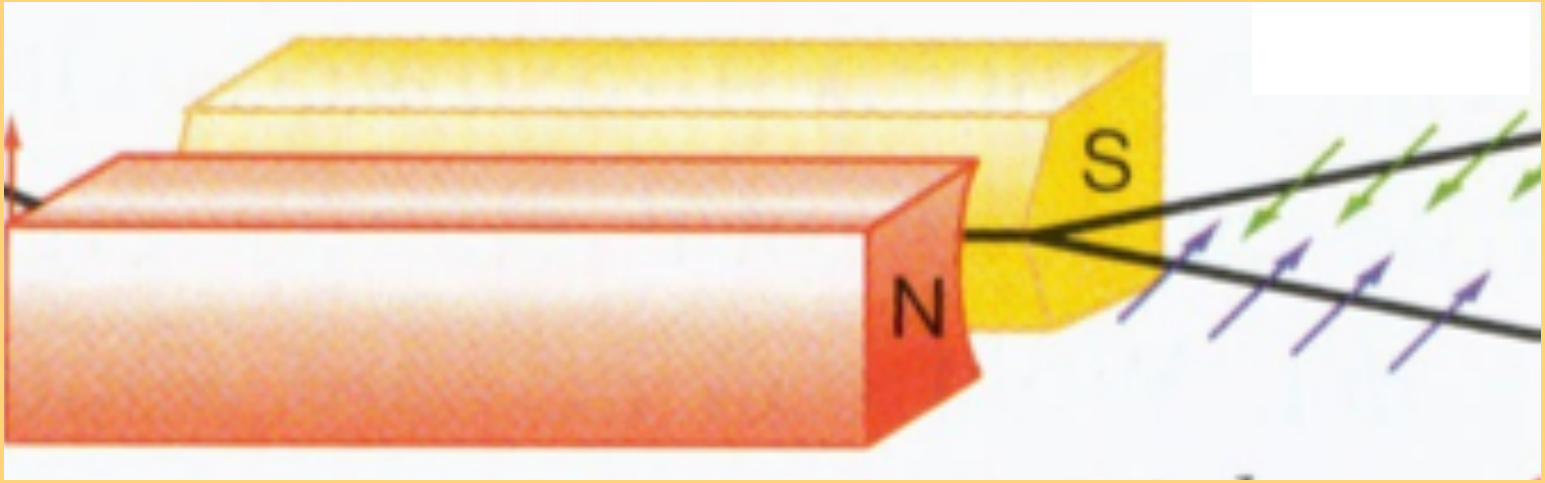

Nonuniform
magnetic field
$m_s = +\frac{1}{2}$
up
down
$m_s = -\frac{1}{2}$
S
N
atom beam


S
N



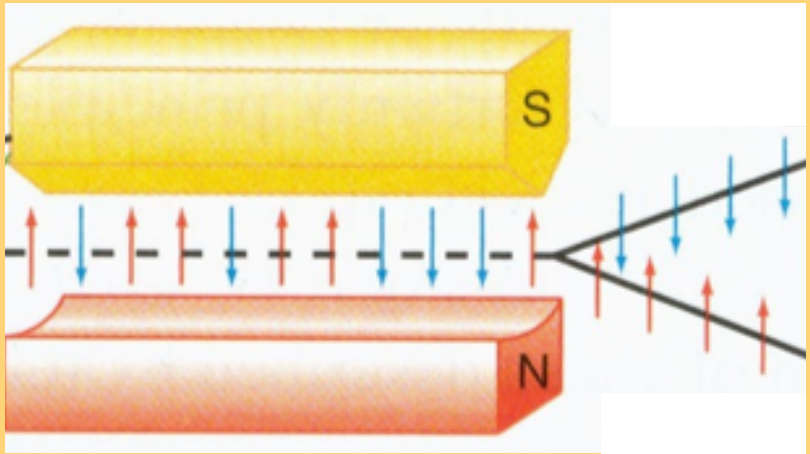
up = u

down = d



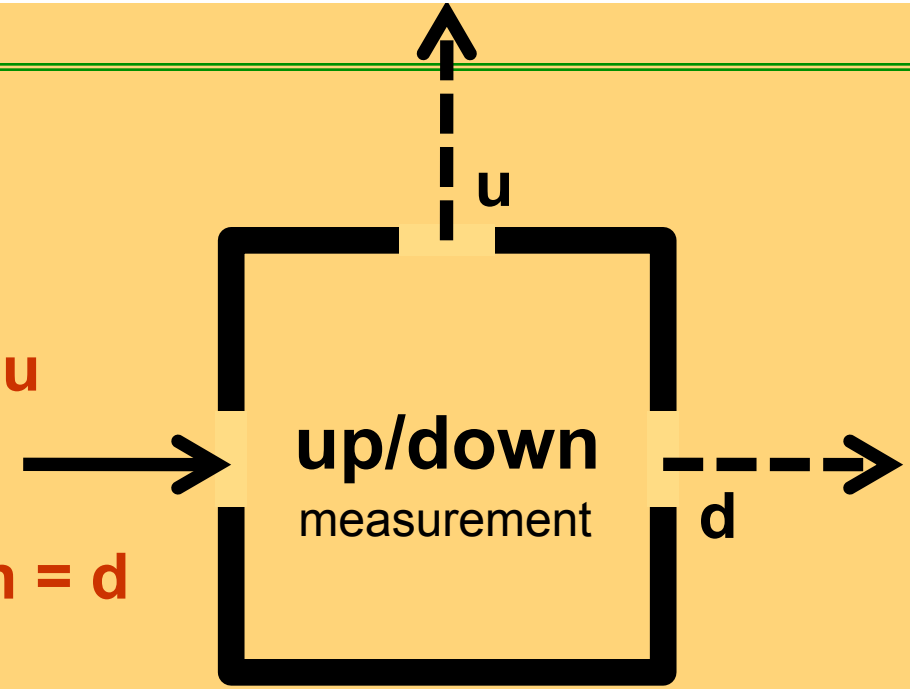
left = ℓ

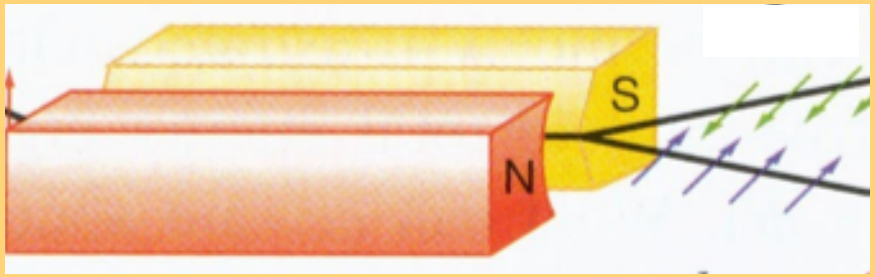
right = r



up = u

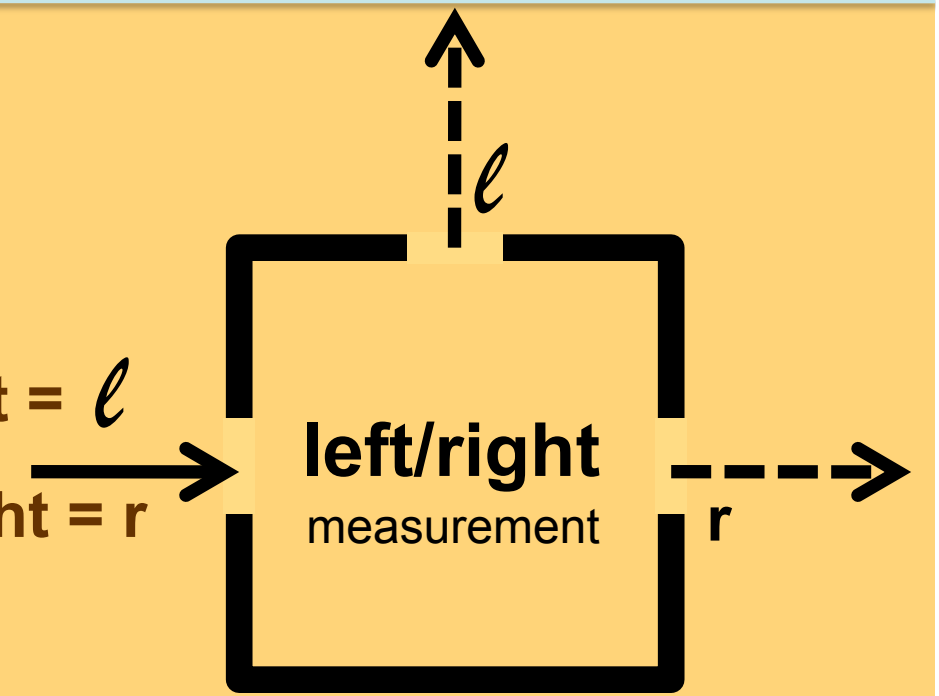
down = d





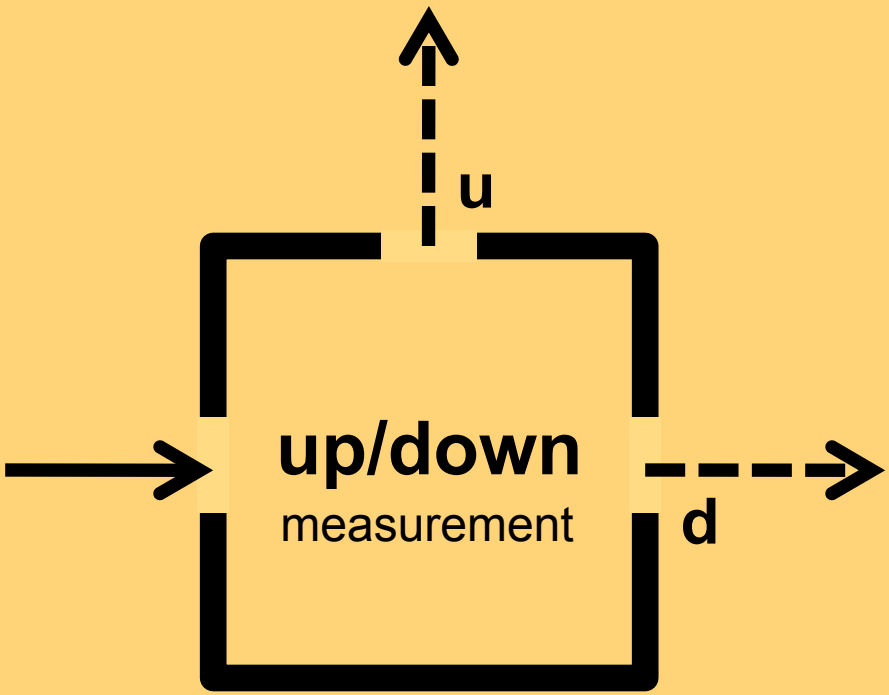
left = ℓ

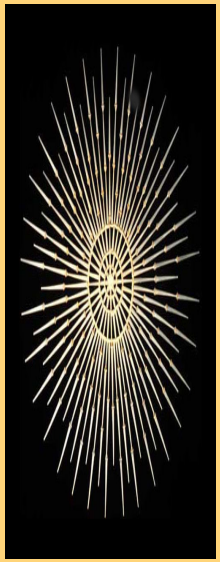
right = r



This device *measures* the up/down property by sending "up" atoms one way and "down" atoms another way.

But to learn the outcome you would have to put a fluorescent screen or something in the beam path:

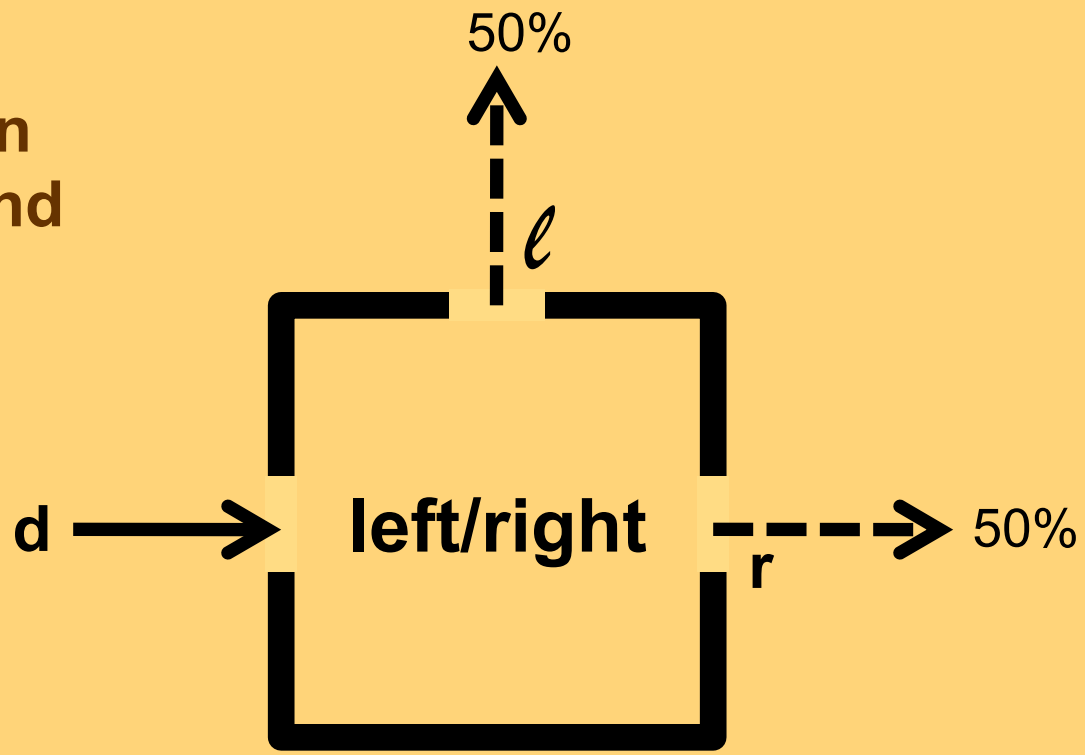




(fluorescent screen lighting up due to particle impact)

Are the up/down and left/right properties of an atom correlated?

No: 50% of down atoms are left and 50% are right

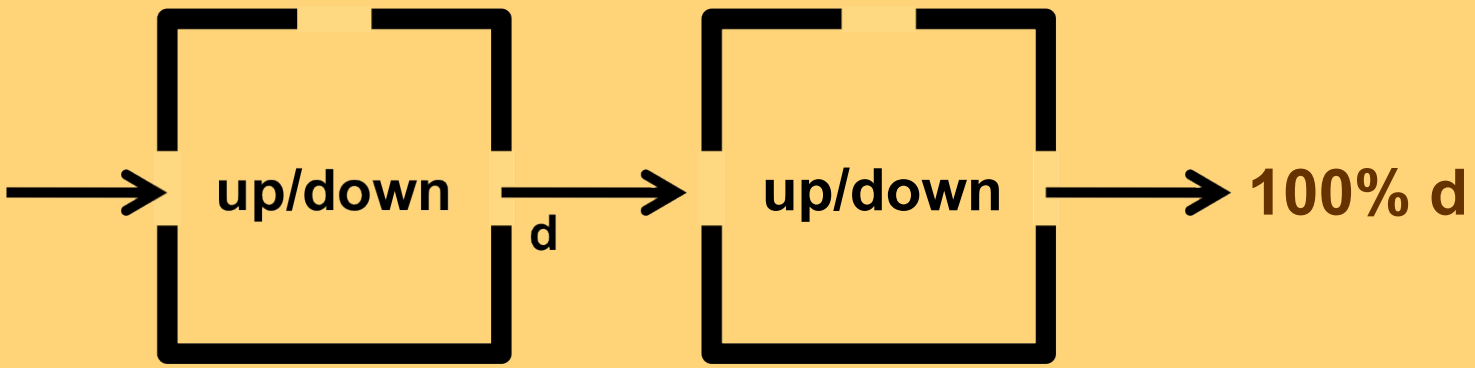


knowing the up/down property of an atom tells us nothing about its left/right property

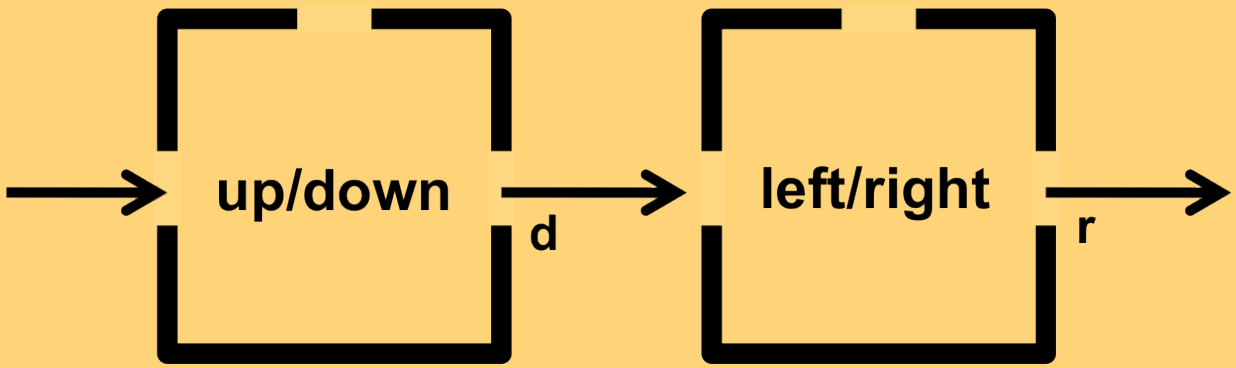
(and no additional information helps [no hidden variables])

Assume a down atom enters a (2nd) up/down device. It is always measured to be "down" by the 2nd device.

(our measurement devices are reliable)

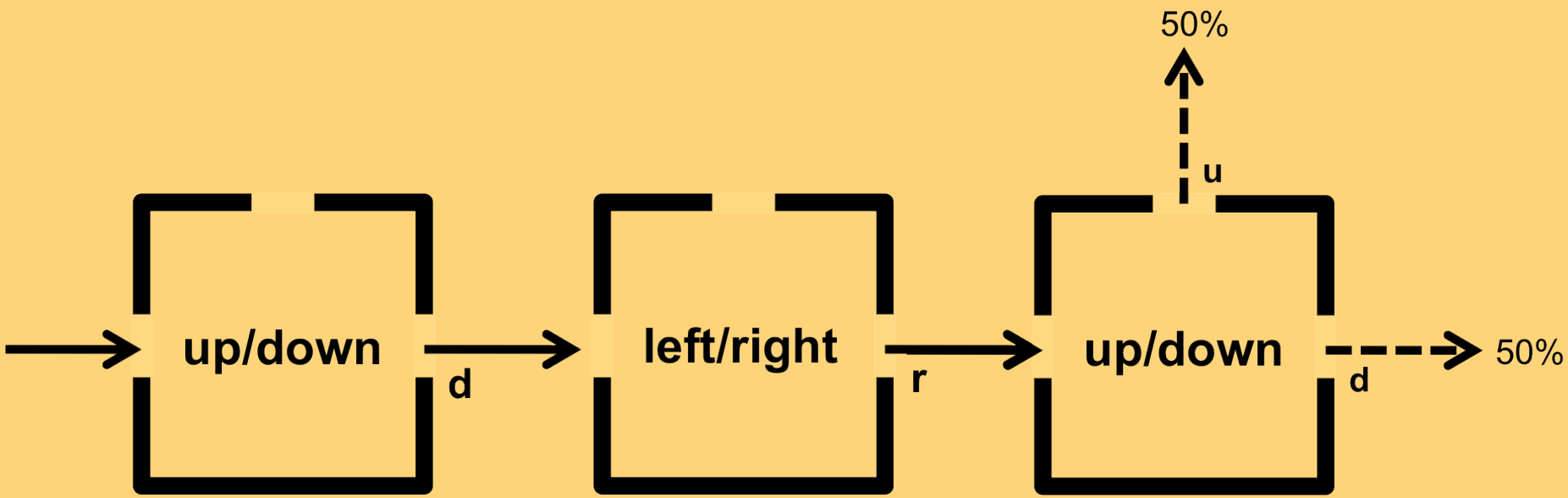


Now assume a down atom emerges from the right aperture of a left/right box (50% will do so).



Let us measure up/down

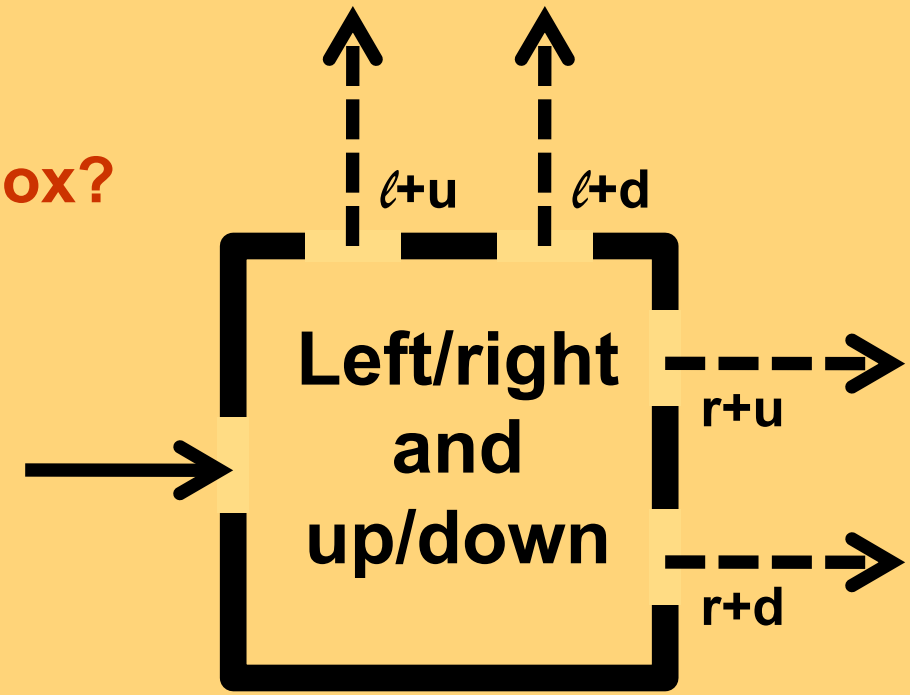
Now assume a down atom emerges from the right aperture of a left/right box (50% will do so).



somehow the left/right box has changed the up/down value !

Can we build a "left/right and up/down" box?

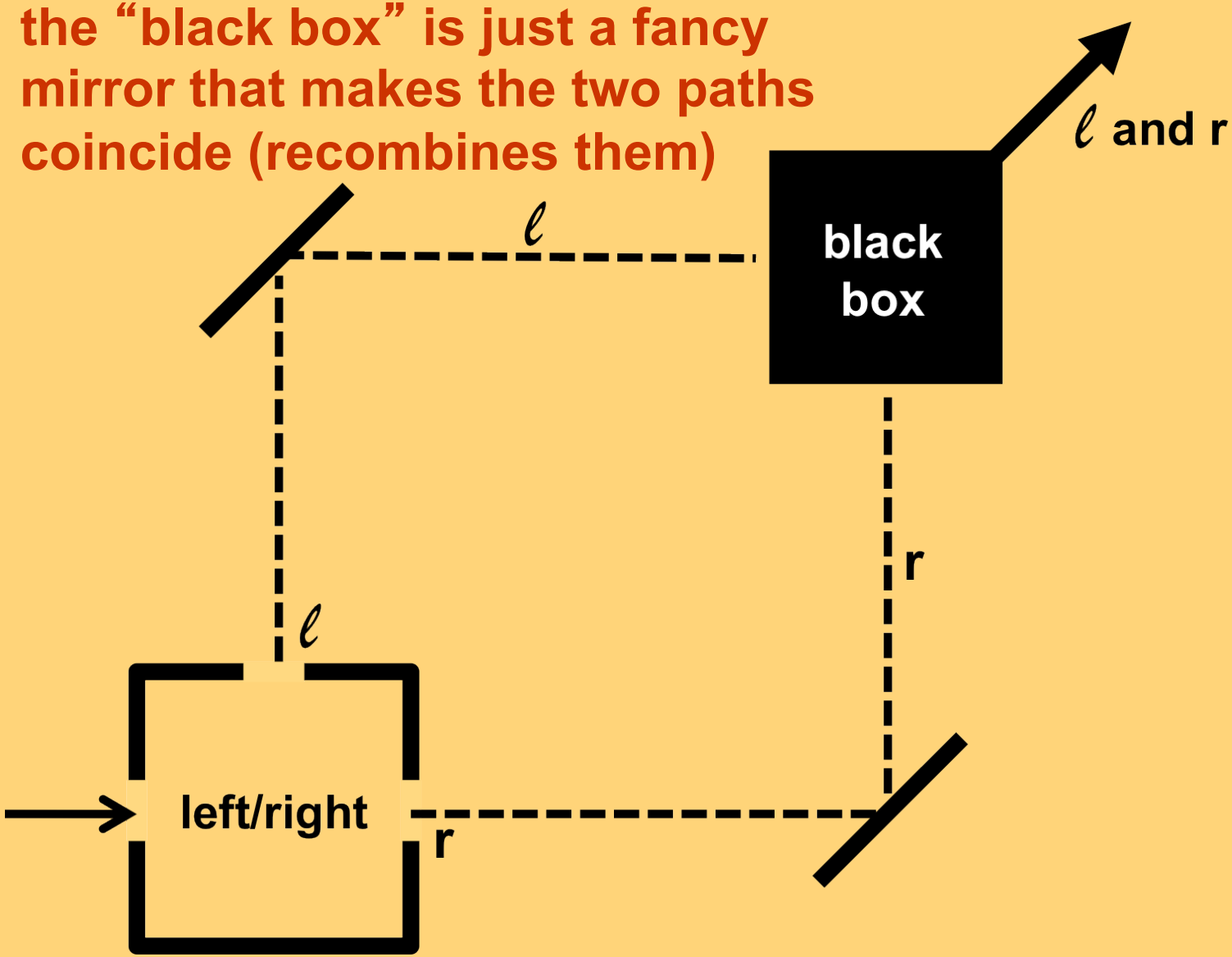
This box would need to consist of a left/right box and a up/down box. But the left/right measurement scrambles the up/down property, and vice versa.



To say "the left/right property of this electron is now such-and-such and the up/down property of this electron is now such-and-such" seems to be fundamentally beyond our means (*uncertainly principle: these are incompatible physical properties*)

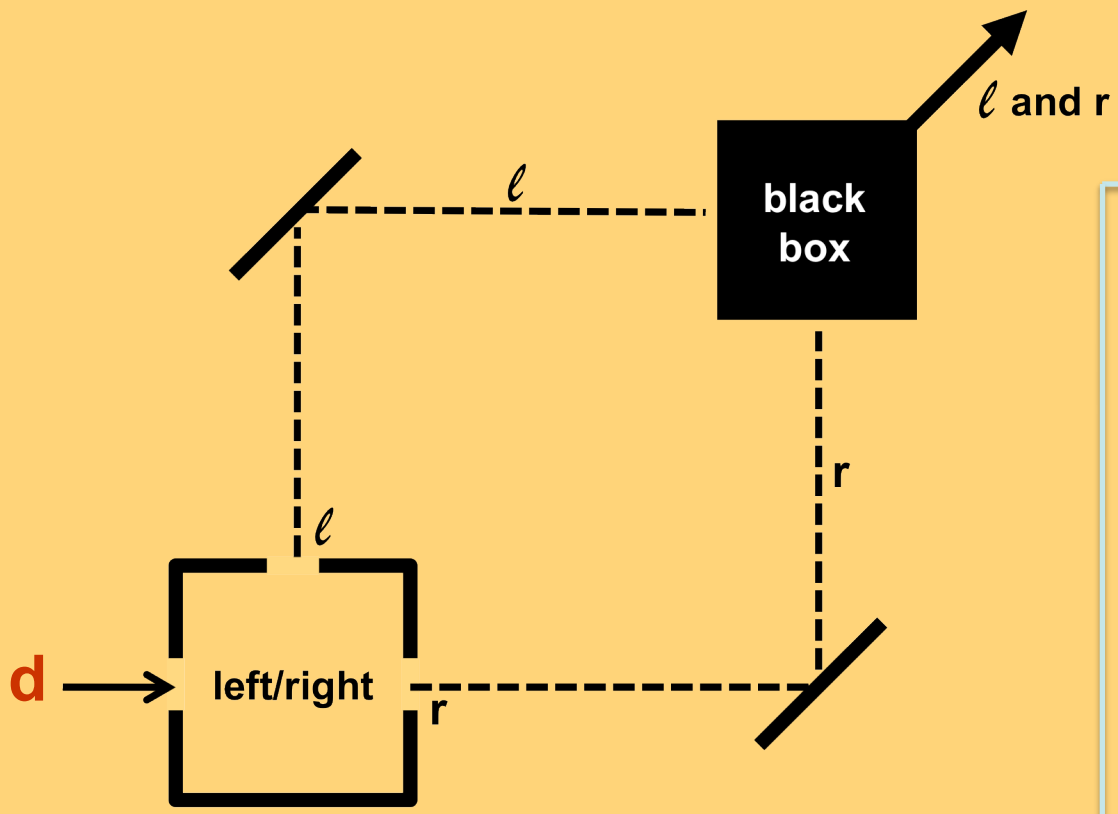
Now construct a more complicated apparatus

the "black box" is just a fancy mirror that makes the two paths coincide (recombines them)

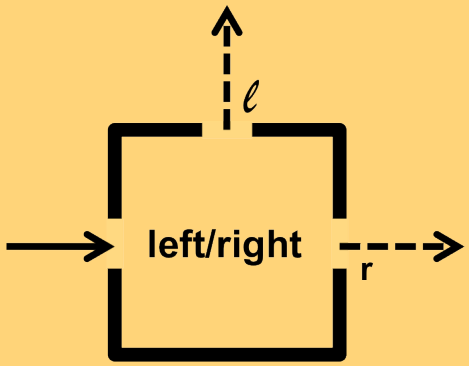


Use a down atom and measure left/right.

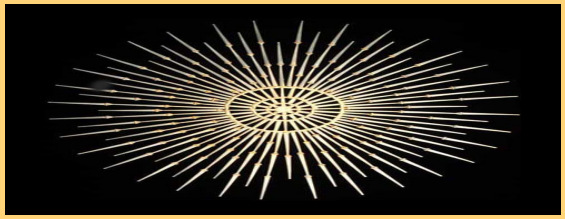
Find 50% ℓ and 50% r



Note: "find" here means using this:

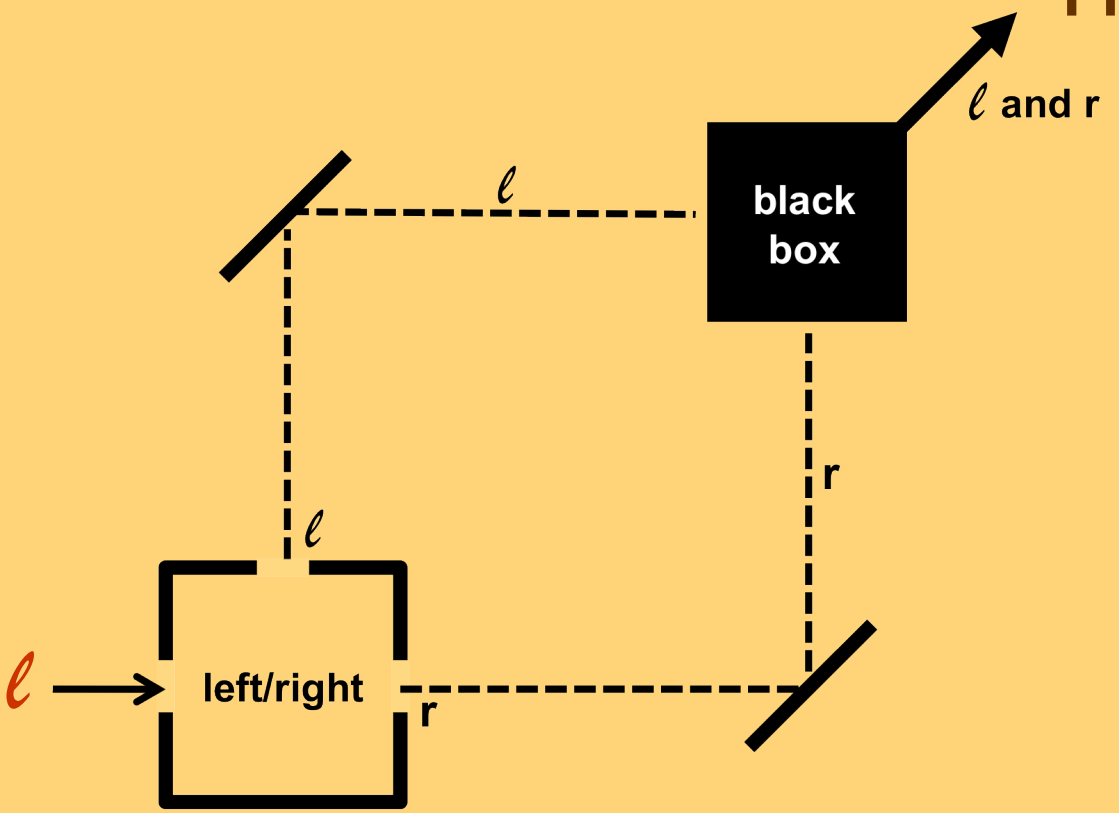


and this:

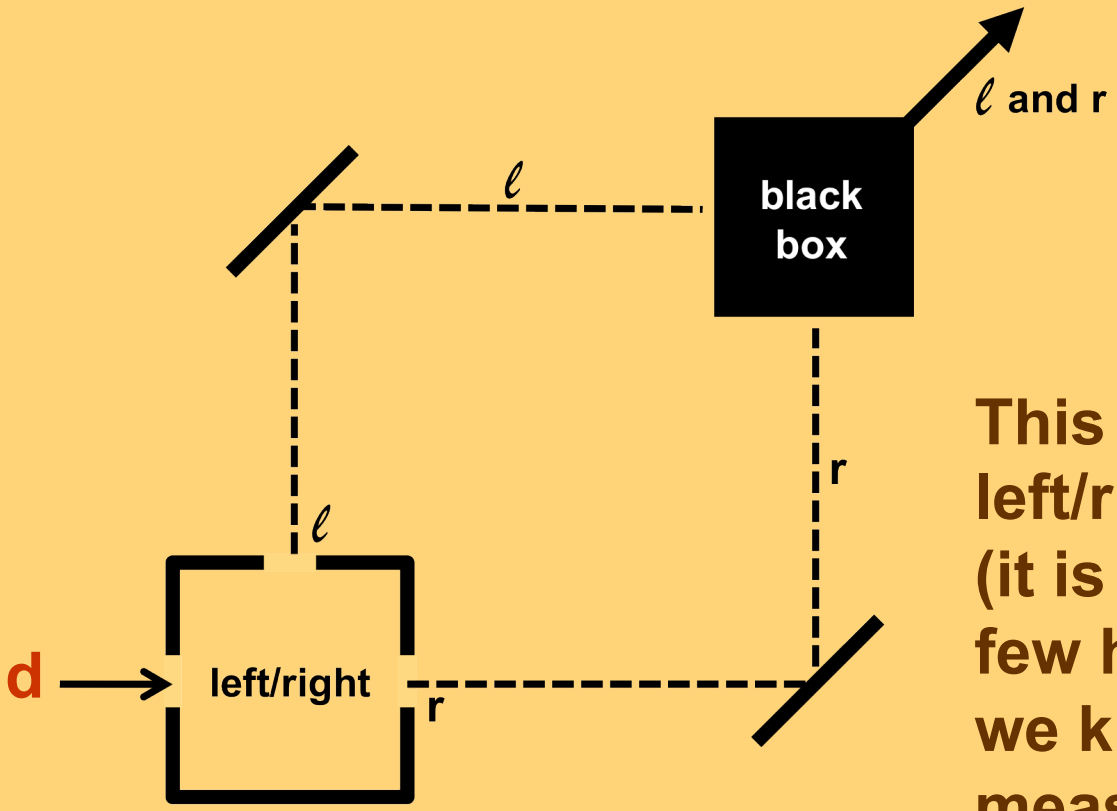


Use a left atom and measure up/down.

Find 50% u and 50% d

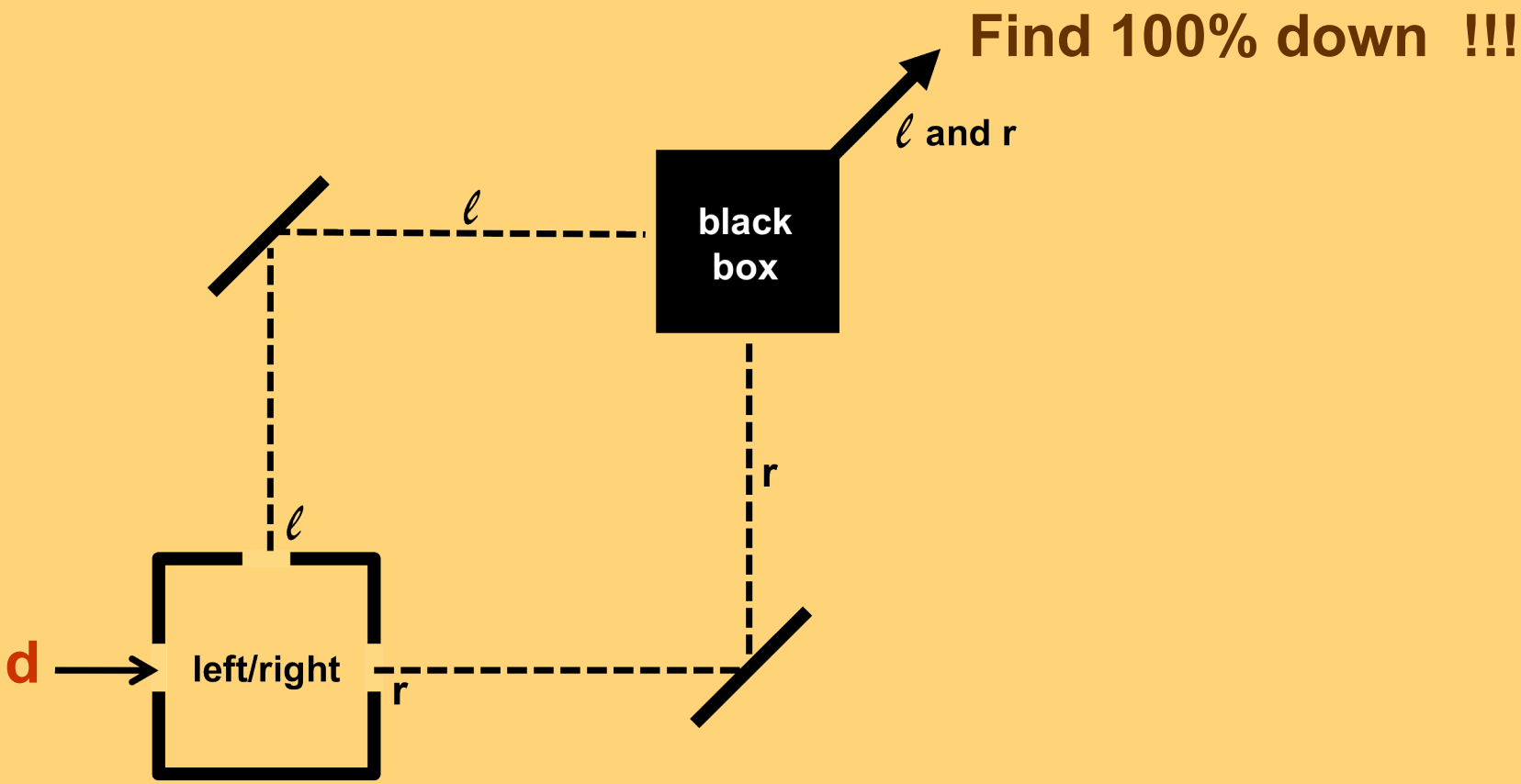


Use a down atom and measure up/down.

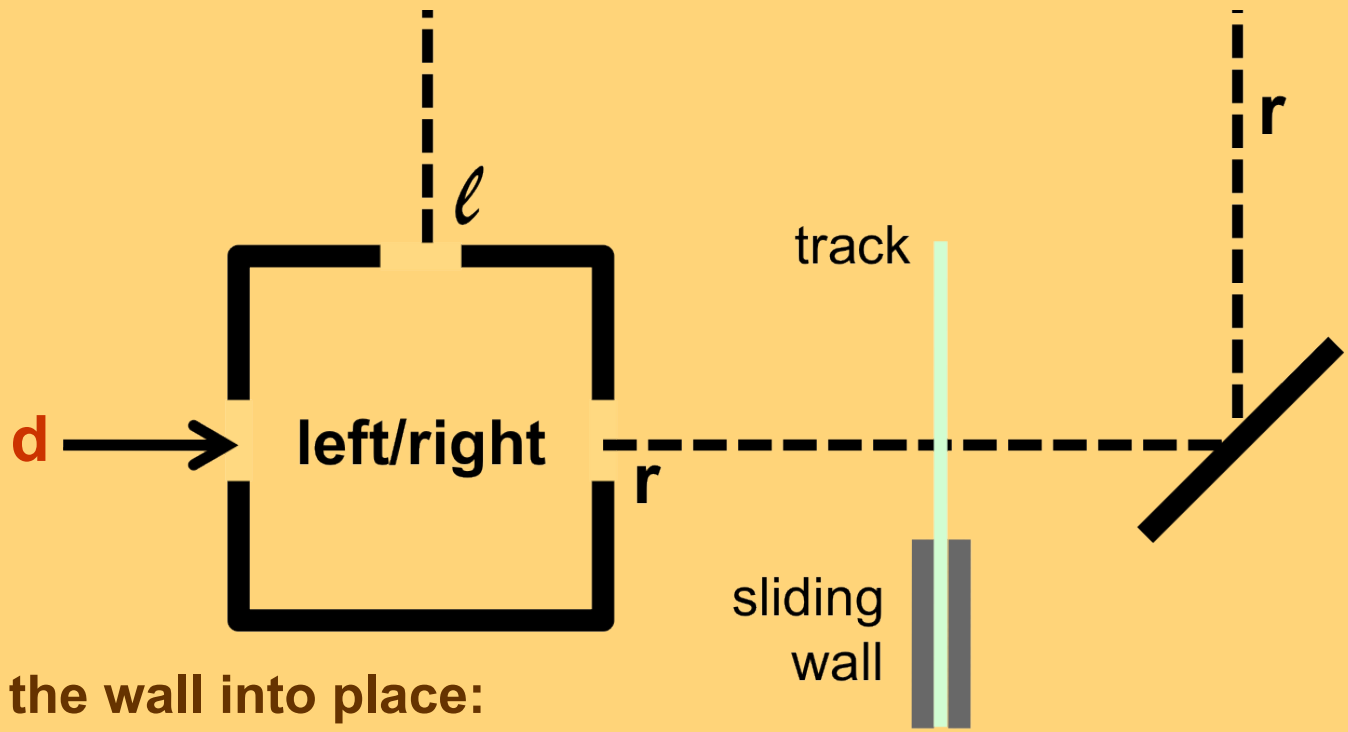


This device is just a fancy left/right box
(it is a left/right box with a few harmless mirrors), and we know a left/right measurement scrambles the up/down property.

Use a down atom and measure up/down.



Let us add a movable wall that absorbs atoms



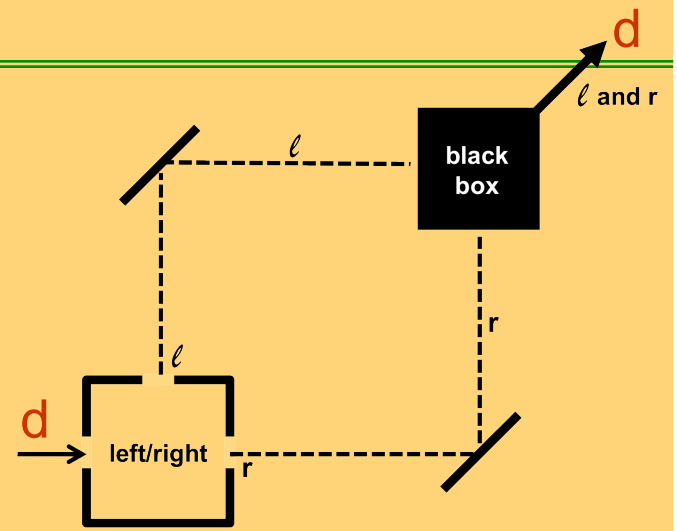
Slide the wall into place:

1.) 50% reduction in the number of atoms emerging from the apparatus

2.) Of the atoms that emerge, their up/down property is now scrambled: 50% u and 50% d.

What can possibly be going on ?

Consider an atom which passes through the apparatus when the sliding wall is out.



Does it take route ℓ ? No, because ℓ atoms have 50/50 u/d statistics.

Does it take route r ? No, same reason.

Can it somehow have taken both routes ? No: if we look (use a fluorescent screen) to see where the atom is inside the apparatus, we find that 50% of the time it is on route ℓ, and 50% of the time it is on route r. We never find two atoms inside, or two halves of a single, split atom, or anything like that. There isn't any sense in which the atom seems to be taking both routes.

Can it have taken neither route? No: if we put sliding walls in place to block both routes, nothing gets through at all.

But these are all the logical possibilities !

What can these atoms be doing?

We use the word (which is just a name for something we don't understand) ***superposition*.**

What we say about an initially down atom which is now passing through our apparatus (with the wall out) is that its not on path ℓ and not on r and not on both and not on neither, but, rather, that its in a *superposition* of being on ℓ <u>and</u> being on r. And what this means (other than "none of the above") we don't know.

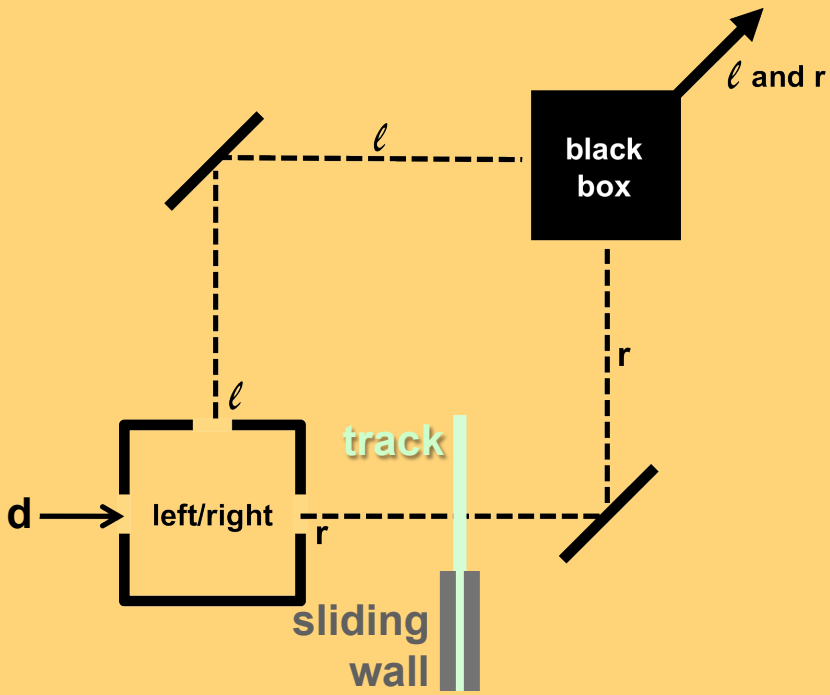
We know, by experiment, that atoms emerge from the left aperture of a left/right box if and only if they are left atoms when they enter that box.

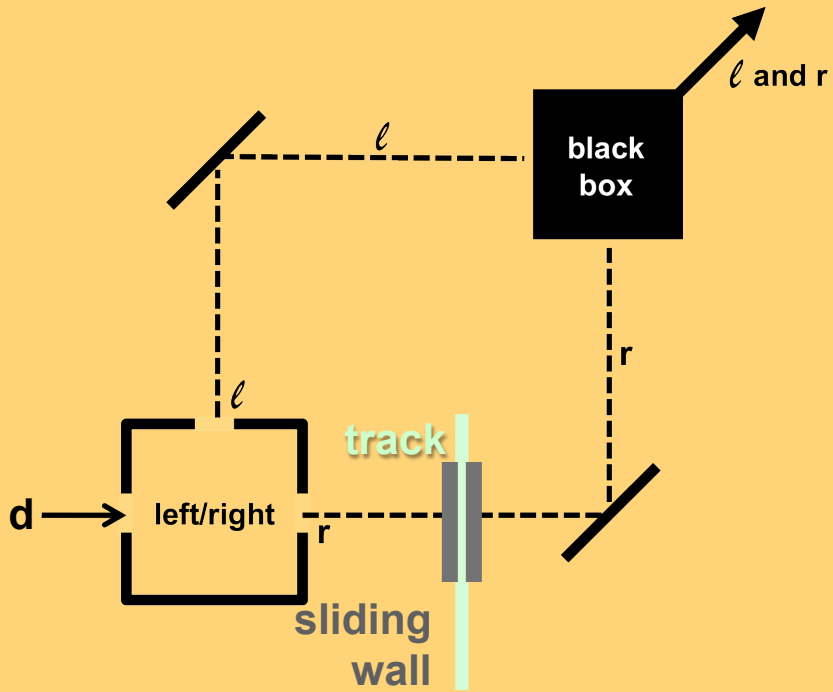
When a *down* atom is fed into a left/right box, it emerges neither through the left aperture nor through the right one nor through both nor through neither. So, it follows that a down atom can't *be* a left one, or a right one, or (somehow) both, or neither. To say that an atom is down must be just the same as to say that its in a *superposition* of being left and right.

So what outcome can we expect of a left/right measurement?

Quantum mechanics must be a probabilistic theory !!

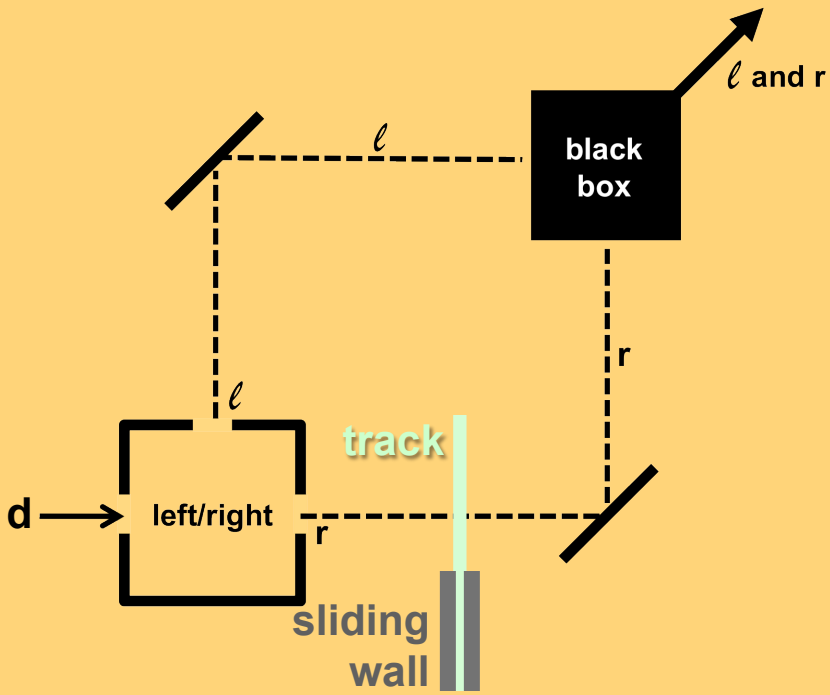
Elitzer-Vaidman bomb testing problem

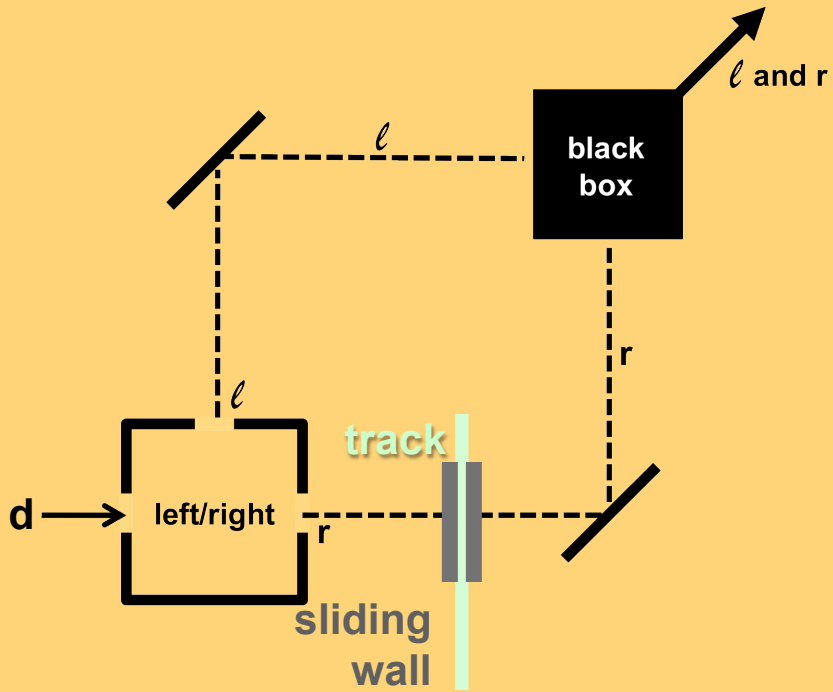




We can tell whether or not the wall is in path *r*

Elitzer-Vaidman bomb testing problem



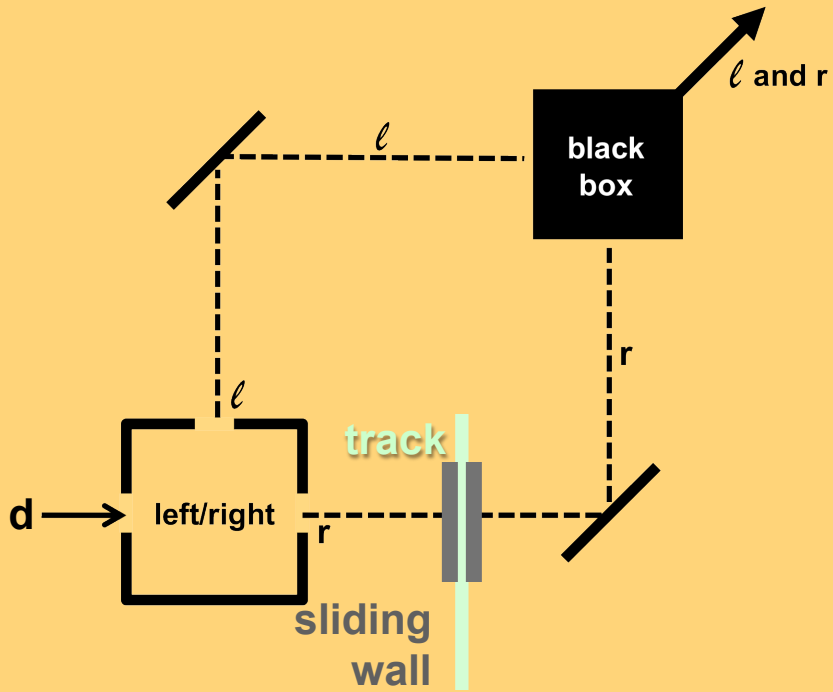


Assume the wall is actually a very sensitive bomb, so sensitive that if an electron hits it, it will explode.

How can we <u>detect</u> the presence of the bomb without setting it off ??

Elitzer-Vaidman bomb testing problem

50% of the time (compared to the bomb not being there) no particle emerges along *ℓ and r*. **The bomb explodes**.

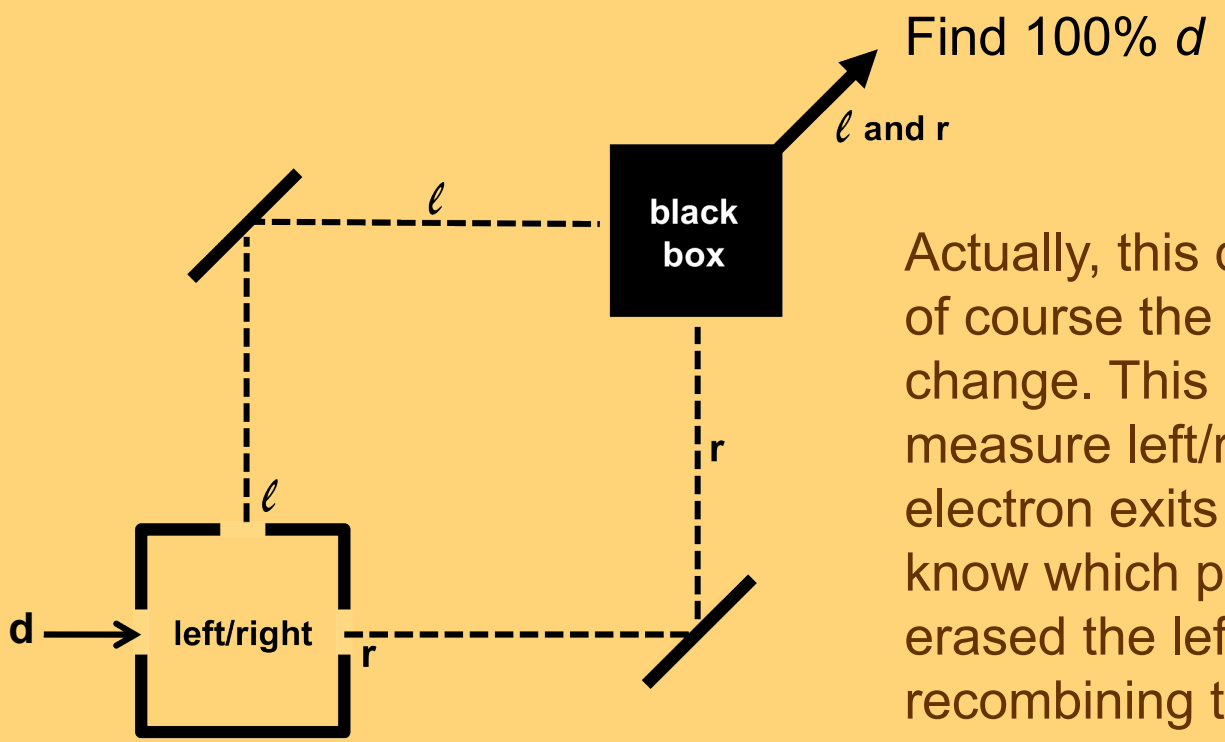


25% of the time, we get a *d* electron out at *ℓ and r*. **We learn nothing** (same result as bomb being absent)

25% of the time, we get a *u* electron out at *ℓ and r*. **We have detected the presence of the bomb without touching it !!!!**

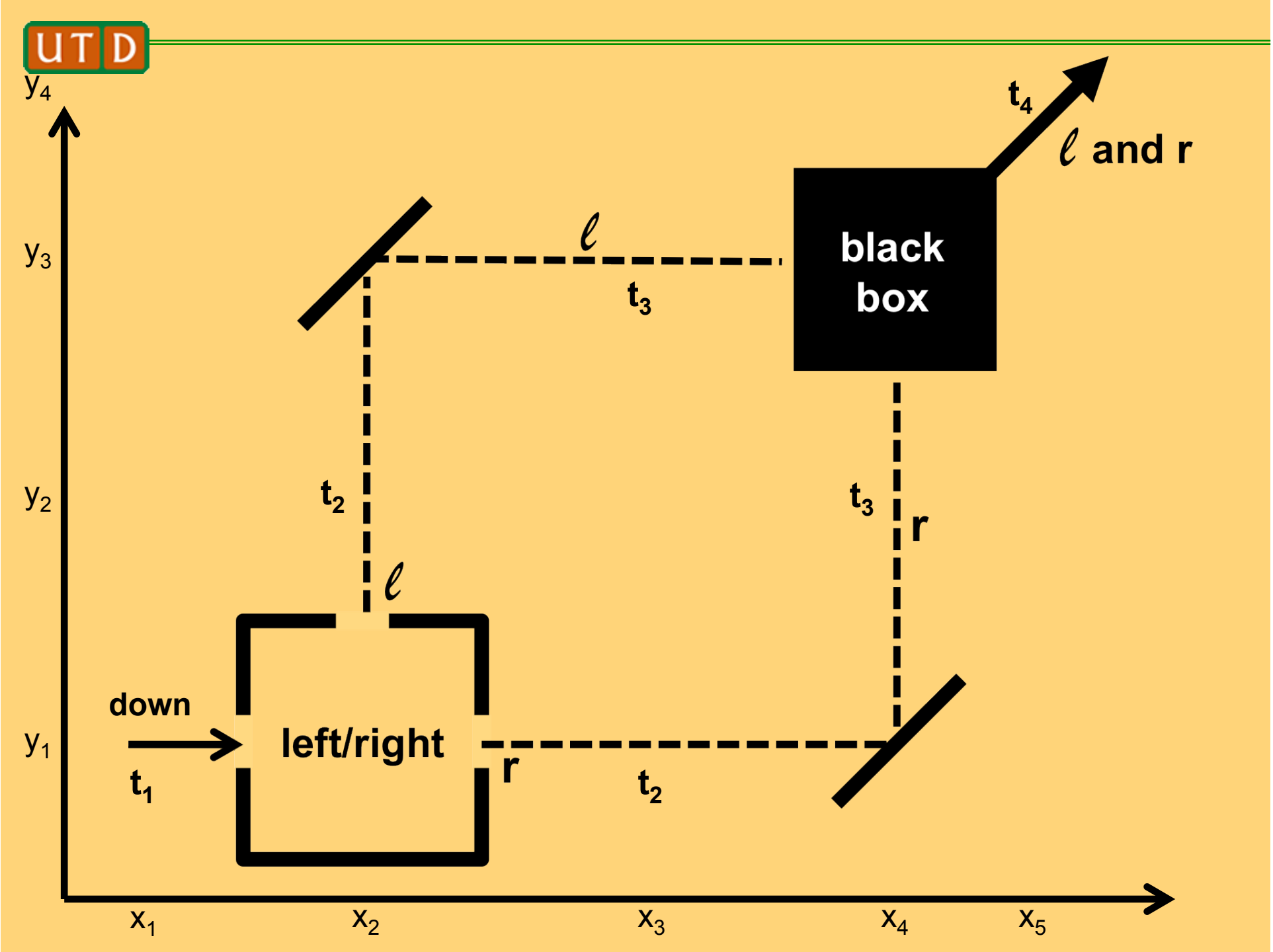
(interaction-free measurement)

Use a *d* electron and measure up/down.



Actually, this device does nothing, so of course the property doesn't change. This device doesn't measure left/right, because when the electron exits the device, we don't know which path it followed! We erased the left/right information by recombining the paths.

In this context the bomb acts as a measuring device – it tells us which path (hence which left/right value) the electron took.


UTD
y_4
y_3
y_2
y_1
t_4
ℓ and r
ℓ
t_3
black box
t_2
t_3
r
ℓ
down
left/right
t_1
r
t_2
x_1
x_2
x_3
x_4
x_5

credit: Lyle Zynda (now at IUSB), PHI 204, Princeton University, Spring 1994

Heisenberg and Von Neumann Interpretation

A physical system's observable properties always have definite values between measurement, but we can never know what those values are since the values can only be determined by measurement, which indeterministically disturbs the system.

This implies that the system was in a definite state before measurement, and that the quantum mechanical formalism gives an incomplete description of physical systems.

Bohr Interpretation (The Copenhagen Interpretation)
(the received view among physicists) (the orthodox interpretation)

It does not make sense to attribute definite values to a physical system's observable properties except relative to a particular kind of measurement procedure, and then it only makes sense when that measurement is actually being performed.

Famously, Bohr proposed an interpretation that denies that the description given by the quantum mechanical formalism is incomplete.

On Bohr's view, the world is divided into two realms of existence, that of quantum systems, which behave according to the formalism of quantum mechanics and do not have definite observable values outside the context of measurement, and of "classical" measuring devices, which always have definite values but are not described within quantum mechanics itself. The line between the two realms is arbitrary.

There are several difficulties with this view, which together constitute the **"measurement problem"**.

To begin with, the orthodox interpretation gives no principled reason why physics should not be able to give a complete description of the measurement process. Indeed, the orthodox interpretation claims that whether a certain physical interaction is a "measurement" is arbitrary, *i.e.*, a matter of choice on the part of the theorist modeling the interaction.

Schrödinger's Cat

Schrödinger pointed out that the orthodox interpretation allows for inconsistent descriptions of the state of macroscopic systems, depending on whether we consider them measuring devices.

Put a cat in an enclosed box along with a device that will release poisonous gas if (and only if) a Geiger counter measures that a certain radium atom has decayed.

The radium atom is in a superposition of decaying and not decaying, and hence the Geiger counter and the cat should also be in a superposition (cat = dead + alive) if we do *not* consider the cat to be a measuring device.

On the other hand, if we consider the cat to be a measuring device, then according to the orthodox interpretation, the cat will either be definitely alive or definitely dead.

Wigner's Idealism: Consciousness As The Cause Of Collapse (Wigner's friend)

Suppose that you put one of Wigner's friends in the box with the cat. The "measurement" you make at a given time is to ask Wigner's friend if the cat is dead or alive.

If we consider the friend as part of the experimental setup, quantum mechanics predicts that before you ask Wigner's friend whether the cat is dead or alive, he is in a superposition of definitely believing the cat is dead and definitely believing that the cat is alive. Wigner argued that this was an absurd consequence of Bohr's view. People simply do not exist in superposed belief-states.

Problem: Wigner's view requires a division of the world into two realms, one occupied by conscious beings who are not subject to the laws of physics, and the other by the physical systems themselves, which evolve deterministically until a conscious being takes a look at what's going on. This is hardly the type of conceptual foundation needed for a rigorous discipline such as physics.

Many other interpretations exist…

When does collapse occur?

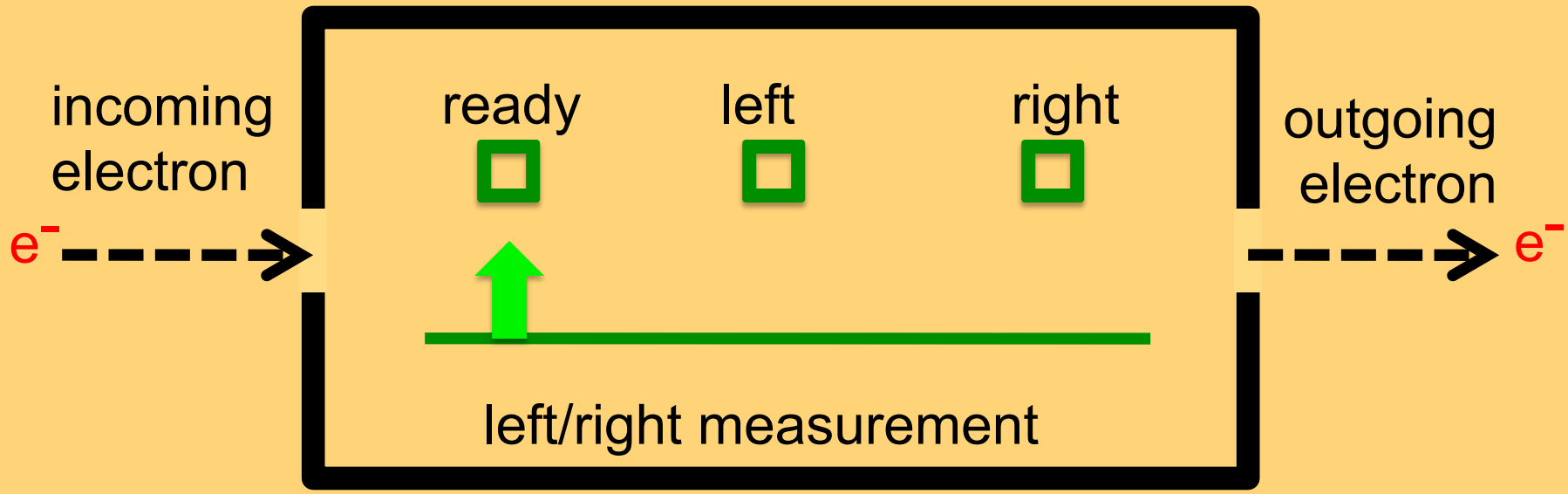
Suppose that Alice has a theory about collapse:

collapse happens immediately after the electron exits the measurement box.

And suppose that Bob has another theory about collapse:

collapse happens later, for example when a human retina or optic nerve or brain gets involved.

Can we decide who is right empirically, that is, by performing some experiment?


incoming
electron
e-
ready
left
right
outgoing
electron
e-
left/right measurement

Can we decide who is right empirically, that is, by performing some experiment?

Here's how to start: Feed a up electron into a left/right device and give it enough time to pass through. If Alice is right, the state of the system is now

either $left^m \phi_l^e$ (with 50% prob.)

or $right^m \phi_r^e$ (with 50% prob.)

whereas if Bob is right, the state of the system is currently

$$\tfrac{1}{\sqrt{2}} left^m \phi_l^e + \tfrac{1}{\sqrt{2}} right^m \phi_r^e$$

so all we need to do is to figure out a way to distinguish, by means of a measurement, these two cases: In one case the pointer points in a particular (but as yet unknown) direction, and in the other case the pointer *isn't* pointing in any particular direction *at all*.

What if we measure the position of the tip of the pointer? That is, let's measure where the pointer is pointing. This won't work.

If Alice is right, of course we will find a 50/50 chance of finding the pointer "pointing-at-left" vs. "pointing-at-right". This is because, according to Alice, the pointer is already in one of those two states.

But if Bob is right, then a measurement of the position of the tip of the pointer will have a 50% change of *collapsing* the wavefunction of the pointer onto the "pointing-at-left" state, and 50% change of collapsing it to "pointing-at-right".

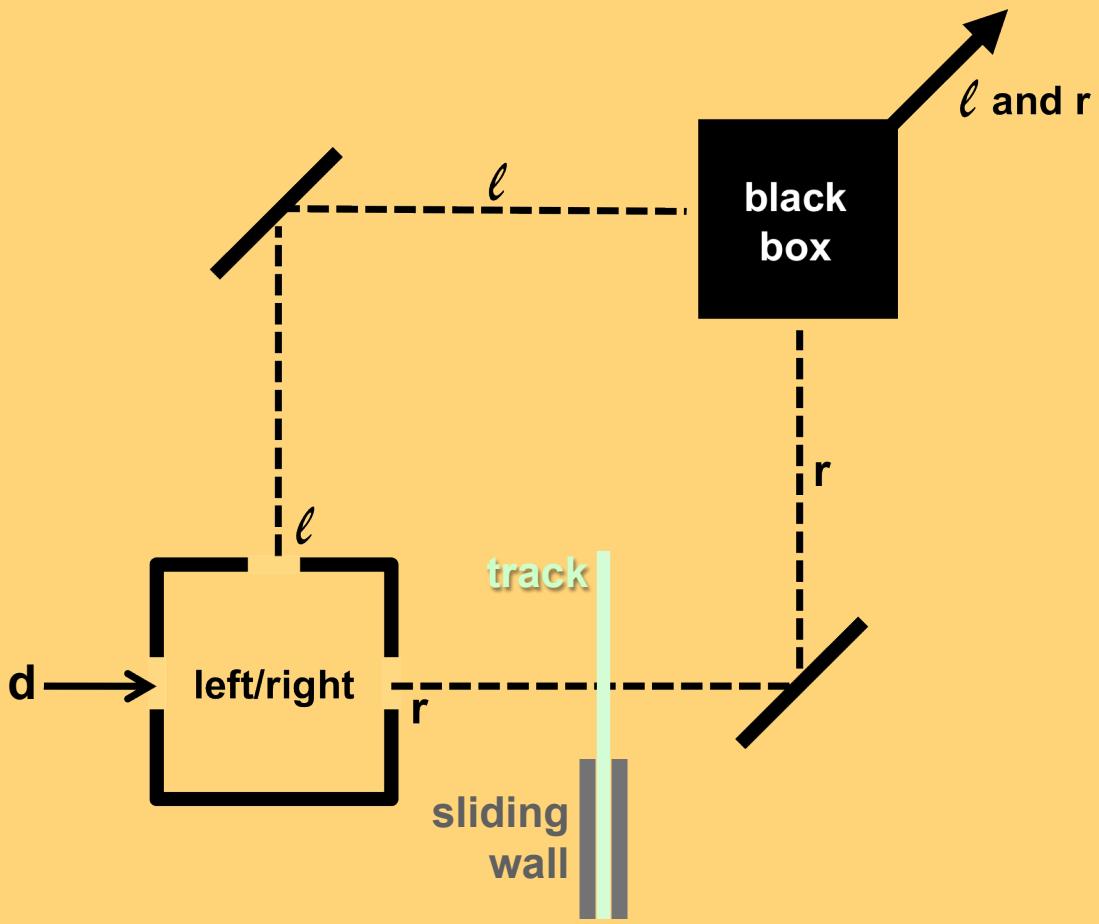
Therefore the probability of any given outcome of a measurement of the position of the pointer will be the *same* for both these theories; and so this isn't the sort of measurement we are looking for.

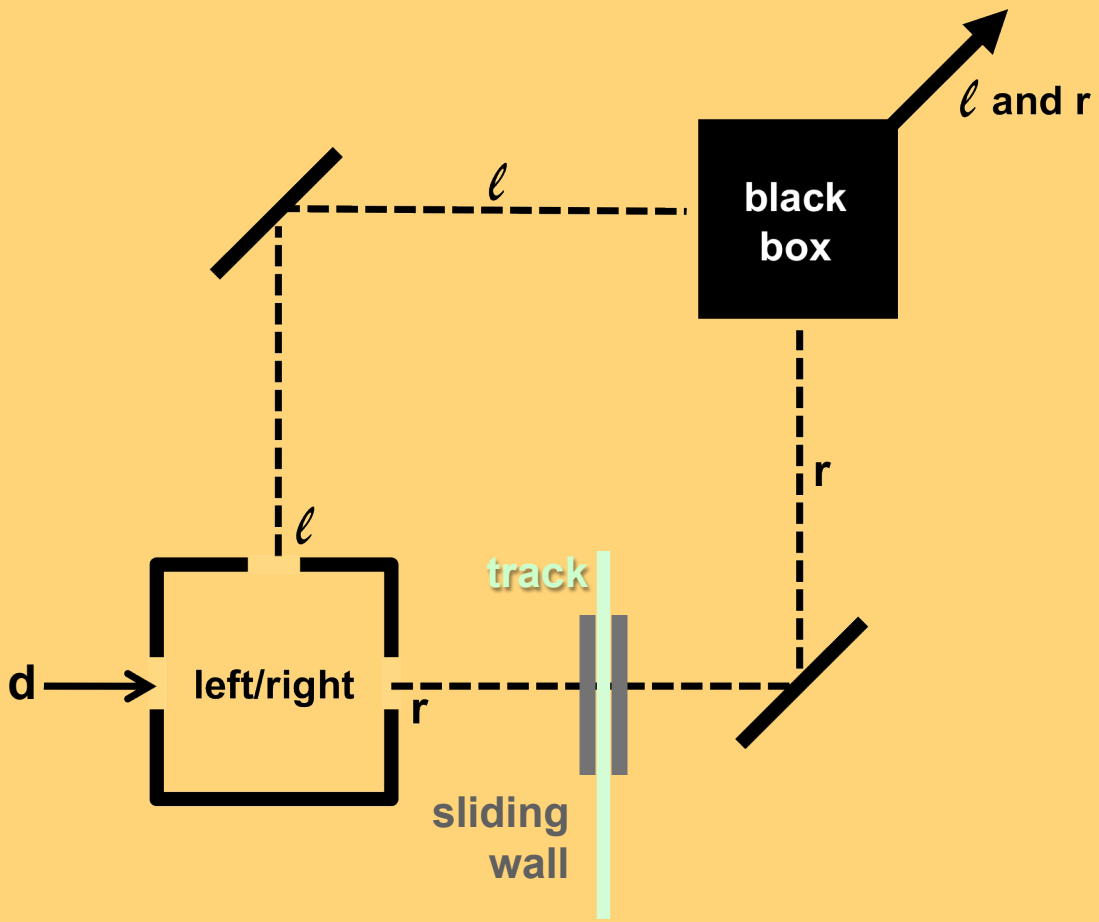
What if we measure the up/down property of the atom?
This won't work.

What if we measure the left/right property of the atom?
This won't work.

These arguments establish that different conjectures about precisely where and precisely when collapse occurs cannot be empirically distinguished from one another.

And so the best we can do at present is to try to think of precisely where and precisely when collapses might *possibly* occur (that is, without contradicting what we *do* know to be true by experiment). But it turns out to be hard to do even that.


ℓ and r
black box
ℓ
r
ℓ
track
d
left/right
r
sliding wall


ℓ and r
black box
ℓ
r
ℓ
track
d
left/right
r
sliding wall