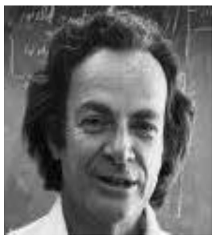


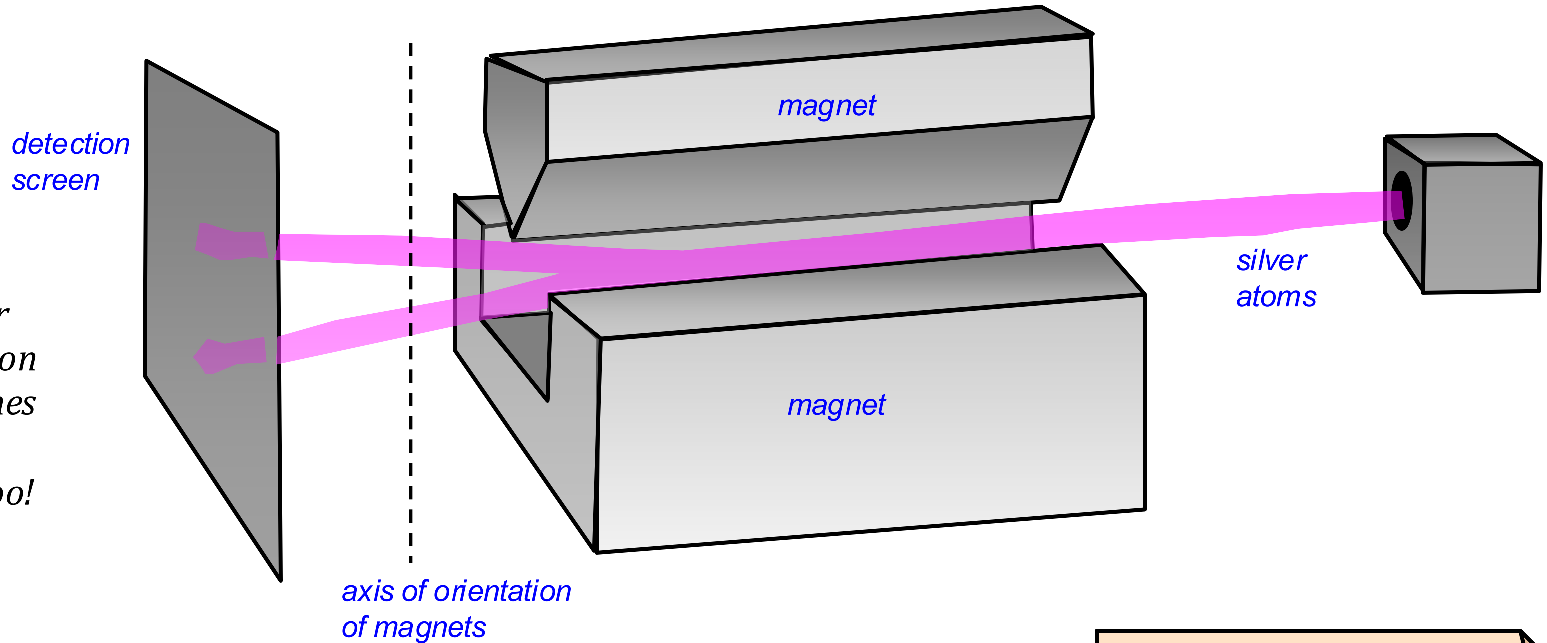
Richard Feynman
(1918-1988)

"I am going to tell you what nature behaves like... Do not keep saying to yourself, if you can possibly avoid it, 'But how can it be like that?' because you will get 'down the drain,' into a blind alley from which nobody has yet escaped. Nobody knows how it can be like that." (*The Character of Physical Laws* 1965, pg. 129.)

02. Classical *vs*. Quantum Systems

1. Stern-Gerlach Experiment (Stern & Gerlach 1922)

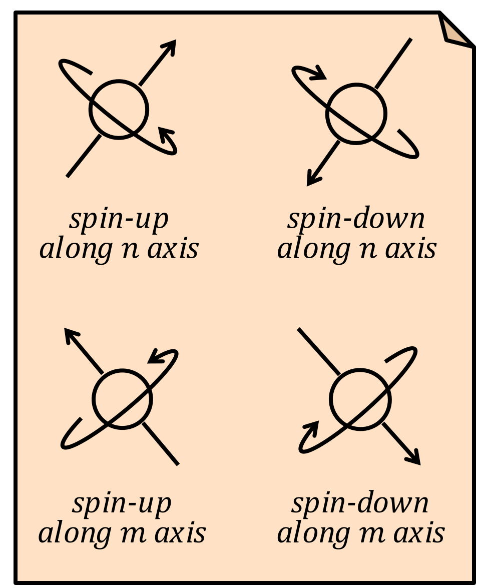
As magnets are rotated (as their axis of orientation rotates), splotches on detection screen rotate, too!



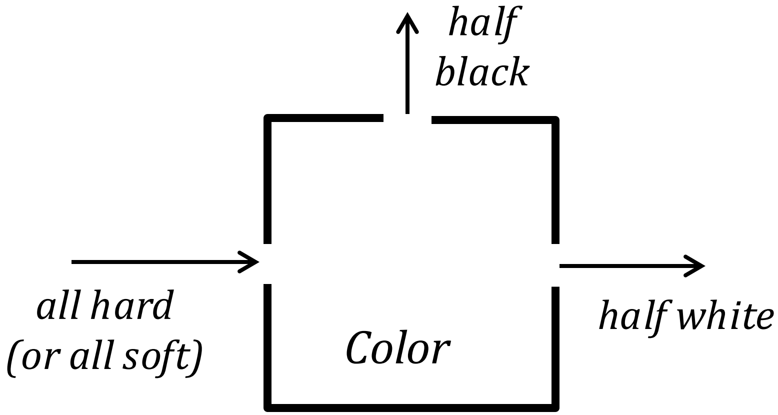
<u>*Suggests*</u>: Electrons possess 2-valued "spin" properties.

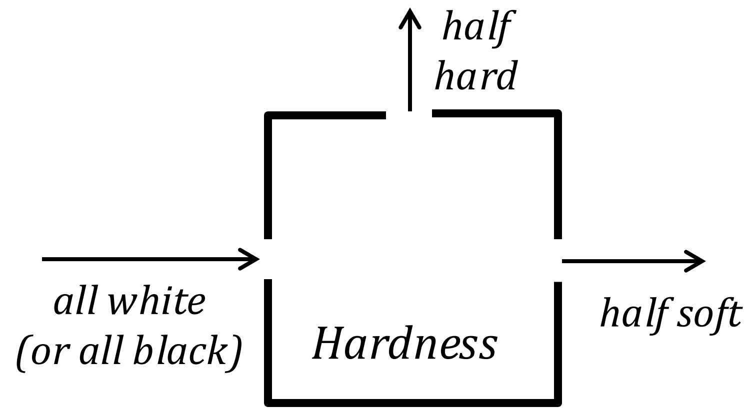
(Goudsmit & Uhlenbeck 1925)

- With respect to a given axis (direction), an electron can possess either the value "spin-up" or the value "spin-down".
- There are as many spin properties as there are possible axes!
- Call two such spin properties with perpendicular axes "Color" (with values *white* and *black*) and "Hardness" (with values *hard* and *soft*).



Experimental Result #1: There is no correlation between Color and Hardness





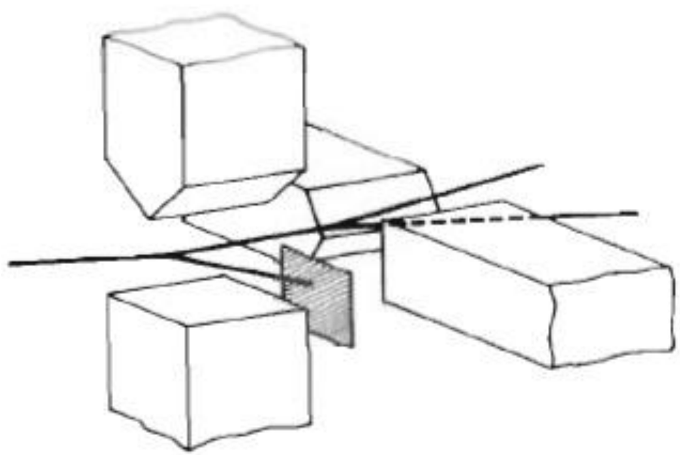
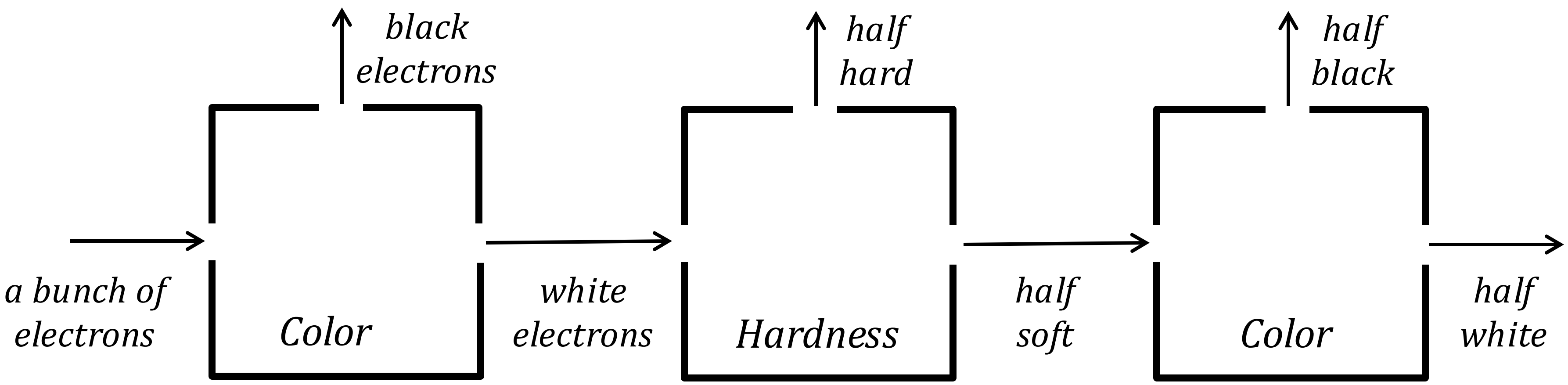


Figure 1.4 Experiment VH.

<u>*Experimental Result #2*</u>:

Hardness measurements "disrupt" Color measurements, and *vice-versa*.



- Can we build a Hardness measuring box that doesn't "disrupt" Color values?
  - *All evidence suggests "No"!*

- Can we determine which electrons get their Color values "disrupted" by a Hardness measurement?
  - *All evidence suggests "No"!*

- <u>*Thus*</u>: All evidence suggests Hardness and Color cannot be simultaneously measured.

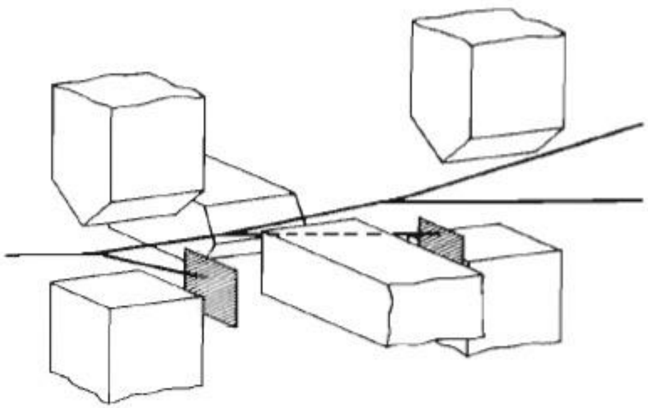
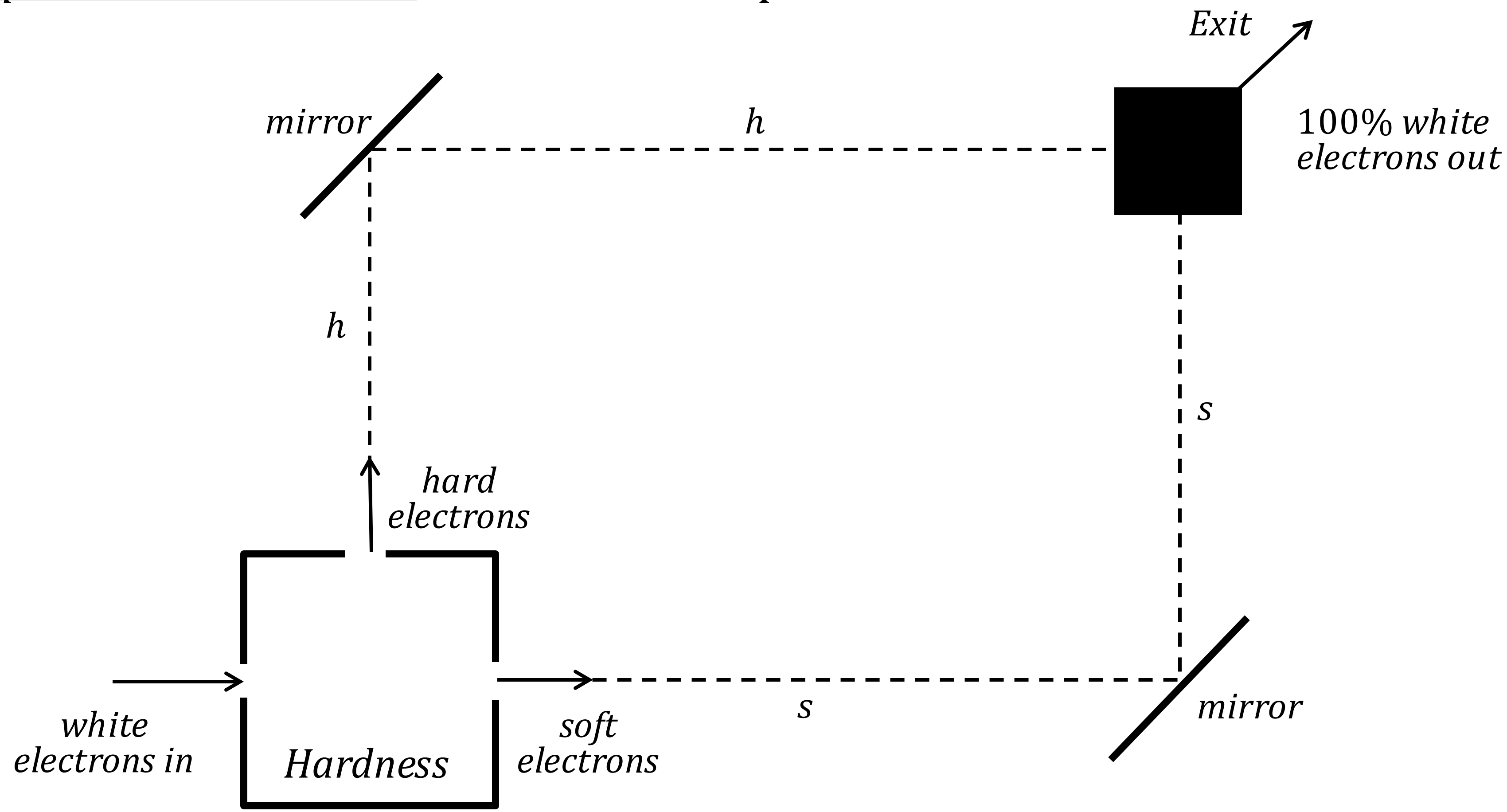


Figure 1.5 Experiment VHV.

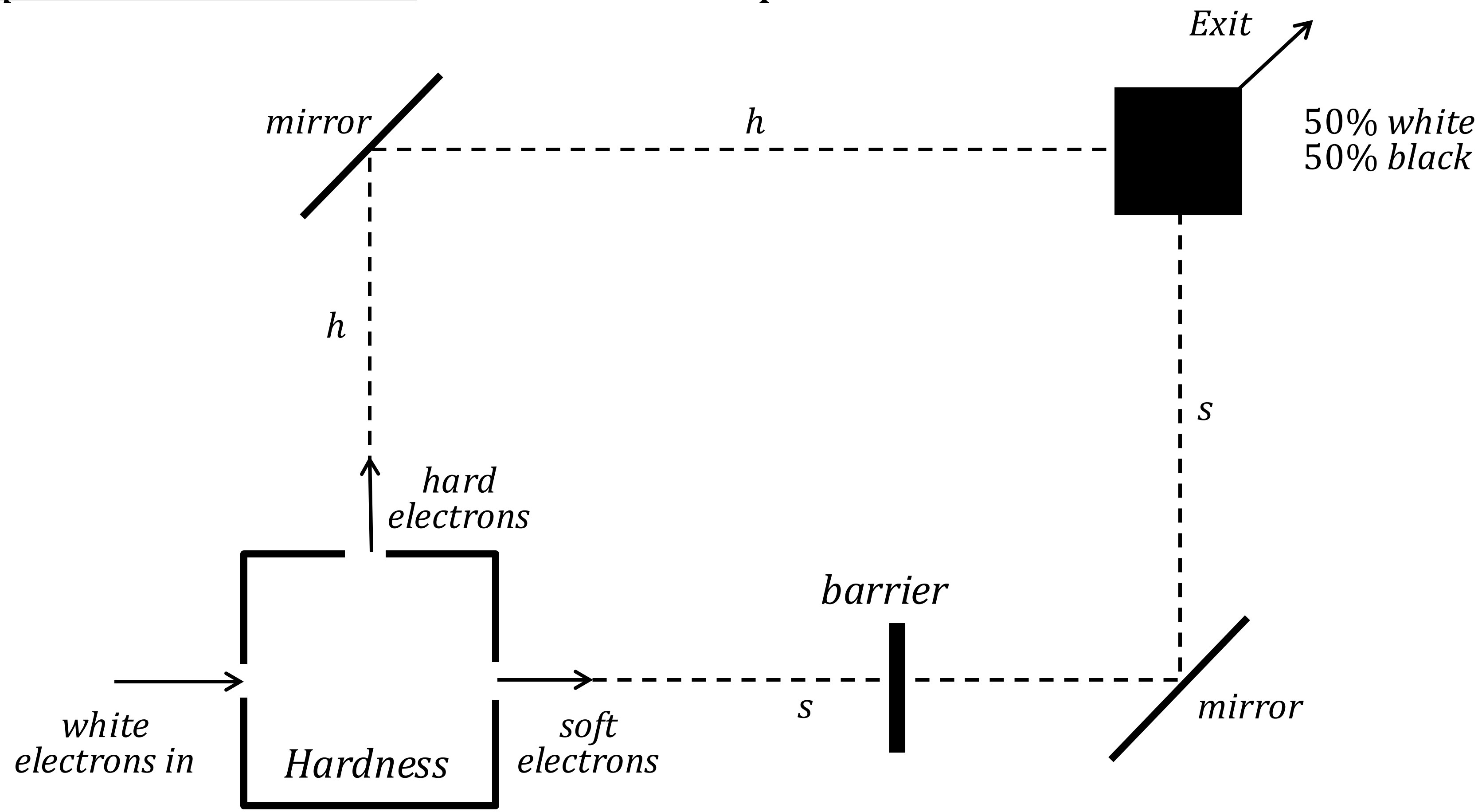
<u>Experimental Result #3</u>: The "2-Path" Experiment.



- Feed white electrons into the device and measure their Color as they exit.
- From previous experiments, we should expect 50% white and 50% black...

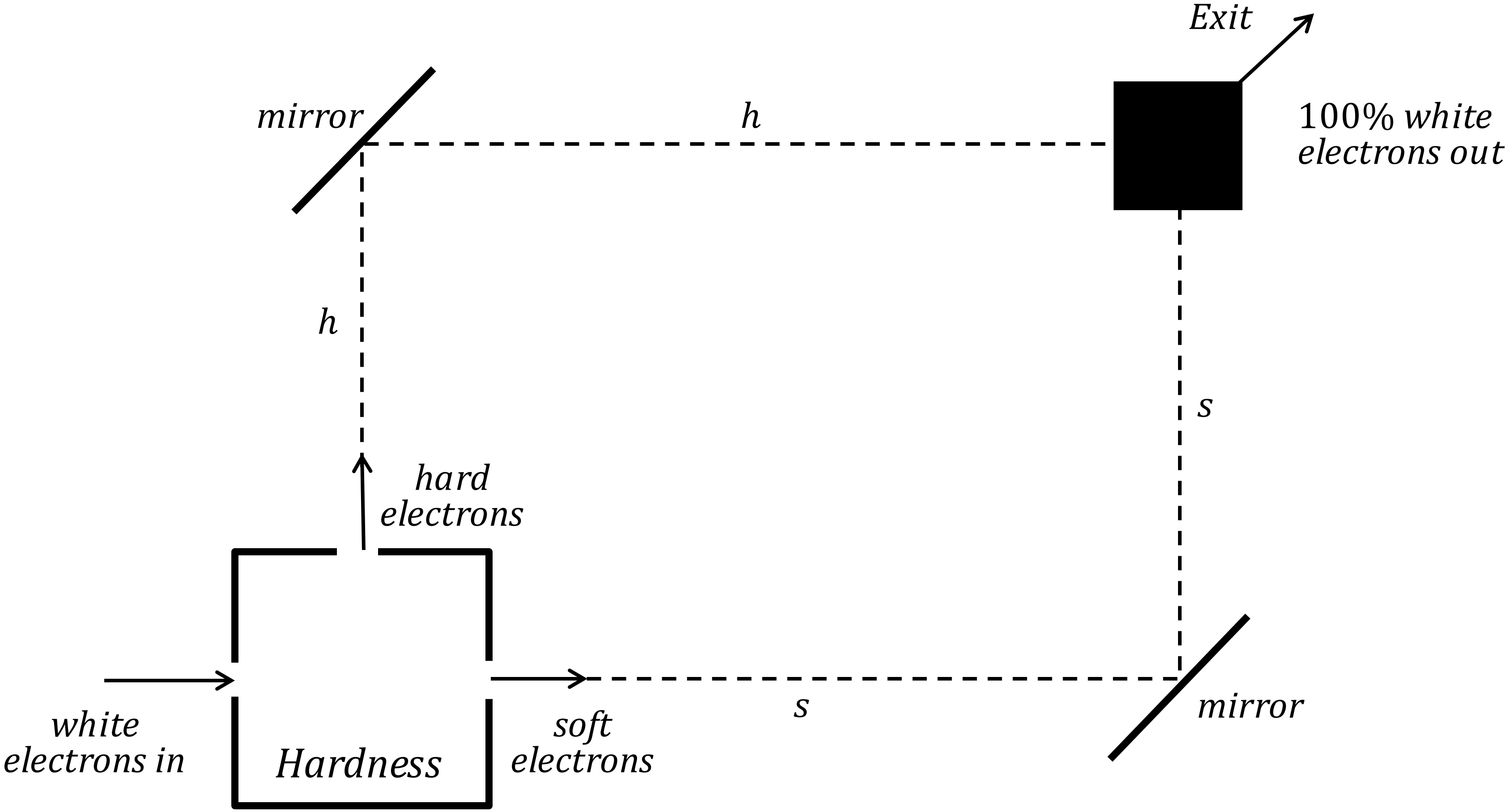
<u>But</u>: Experimentally, 100% are white!

Experimental Result #3: The "2-Path" Experiment.



- Now insert a barrier along the *s* path.
- 50% less electrons register at the Exit.
- *And*: Experimentally, of these 50% are white and 50% are black.

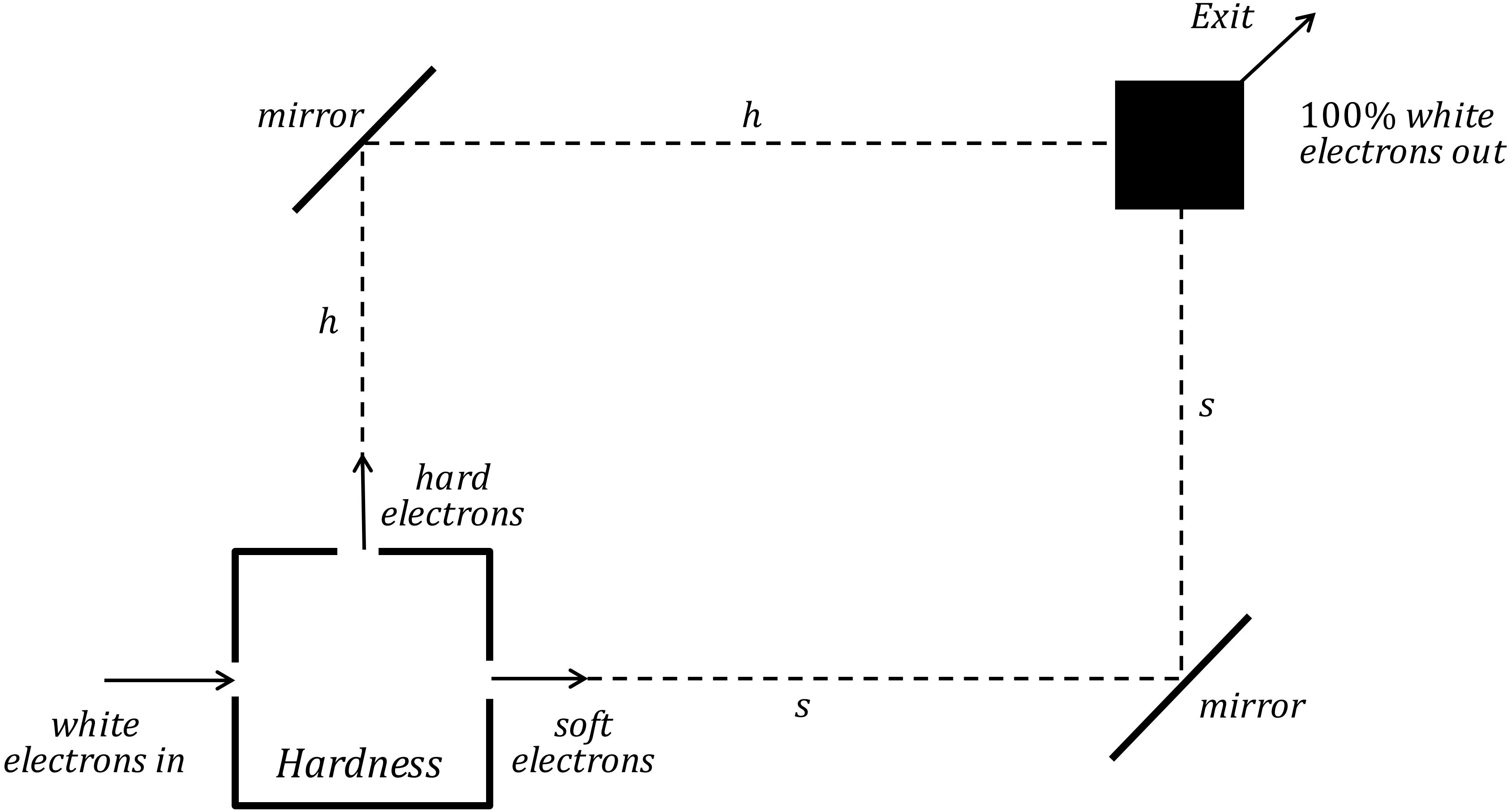
Experimental Result #3: The "2-Path" Experiment.



What path does an individual electron take without the barrier present?

- Not *h*. The Color statistics of hard electrons is 50/50.
- Not *s*. The Color statistics of soft electrons is 50/50.
- Not *both*. Place detectors along the paths and only one will register.
- Not *neither*. Block both paths and no electrons register at Exit.

Experimental Result #3: The "2-Path" Experiment.



What path does an individual electron take without the barrier present?

- Not *h*.
- Not *s*.
- Not *both*.
- Not *neither*.

Suggests that white electrons have no determinate value of Hardness.

2. How to Describe Physical Phenomena: 5 Basic Notions

(a) **Physical system**.

Classical example: baseball

Quantum example: electron

(b) **Properties** of a physical system.

Classical examples
- momentum
- position
- energy

Quantum examples
- Hardness (spin along a given direction)
- Color (spin along another direction)
- momentum
- position
- energy

(c) **State** of a physical system. Description of system at an instant in time in terms of its properties.

Classical example
- baseball moving at 95mph, 5 ft from batter.

Quantum example
- white electron entering a Hardness box.

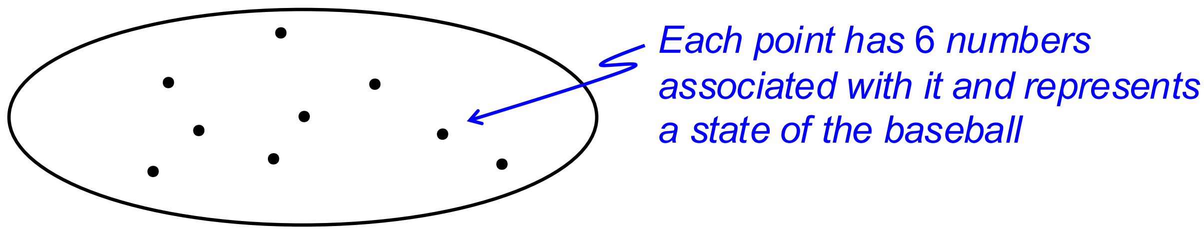
(d) **State space**. The collection of all possible states of a system.

(e) **Dynamics**. A description of how the states of a system evolve in time.

Mathematical Description of Classical Physical System
(*Baseball example)*

(i) A **state** of the baseball: Specified by giving *momentum* (p_1, p_2, p_3) and *position* (q_1, q_2, q_3). (Baseball has 6 "degrees of freedom".)

(ii) The **state space** of the baseball: Represented by a 6-dim *set of points* (*phase space*):



(iii) **Properties** of the baseball: Represented by *functions* on the phase space. *These are in-principle <u>always well-defined</u> for any point in phase space.*

<u>*Ex*</u>: baseball's *energy* $= E(p_i, q_i) = (p_1{}^2 + p_2{}^2 + p_3{}^2)/2m$

(iv) **Dynamics** of the baseball: Provided by Newton's equations of motion (in their Hamiltonian form).

Will this mathematical description work for electrons?

No!

- Experiments suggest the "spin" properties of Hardness and Color are not always well-defined.
- *So*: We can't represent them mathematically as functions on a set of points.

- *Early 20th century task*: Construct a new theory (quantum mechanics) for physical systems like electrons that represents states, state space, and properties in a different way than classical mechanics:

physical concept	*mathematical representation*	
	Classical mechanics	*Quantum mechanics*
states	points	vectors
state space	set of points (phase space)	vector space
properties	functions of points	operators on vectors