Title: Where is the quantum particle between two measurements

Date: Mar 16, 2010 04:30 PM

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Abstract: The Wheeler delayed choice experiment, Elitzur-Vaidman interaction-free measurement, and Hosten-Kwiat counterfactual computation will be discussed to answer Bohr's forbidden question: "Where is a quantum particle while it is inside a Mach-Zehnder Interferometer?". I will argue that the naive application of Wheeler's approach fails to explain a weak trace left by the particle and that the two-state vector description is required.

TEL AVIV UNIVERSITY אוניברסיטת תל-אביב

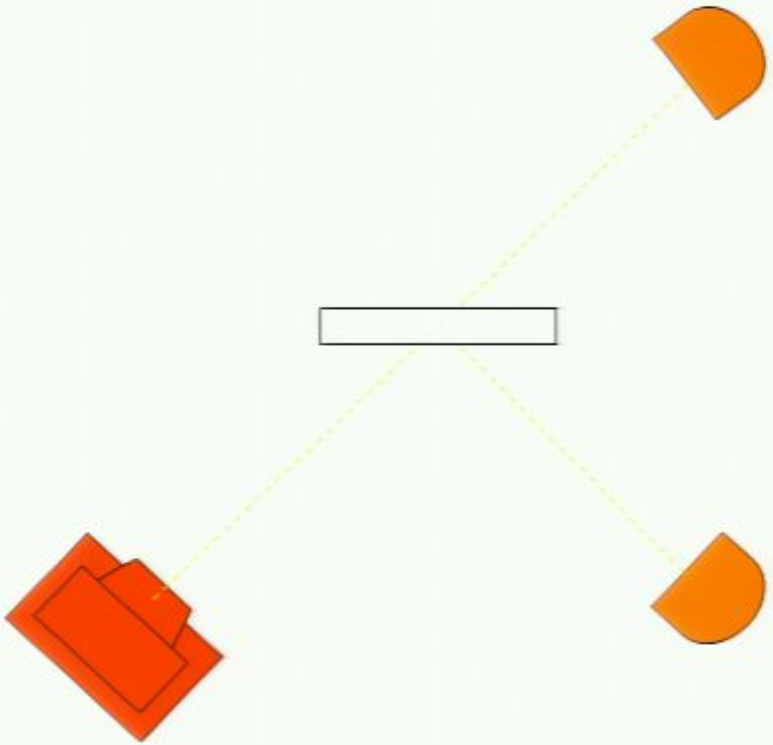
Where Is the Quantum Particle between Two Measurements?

Lev Vaidman

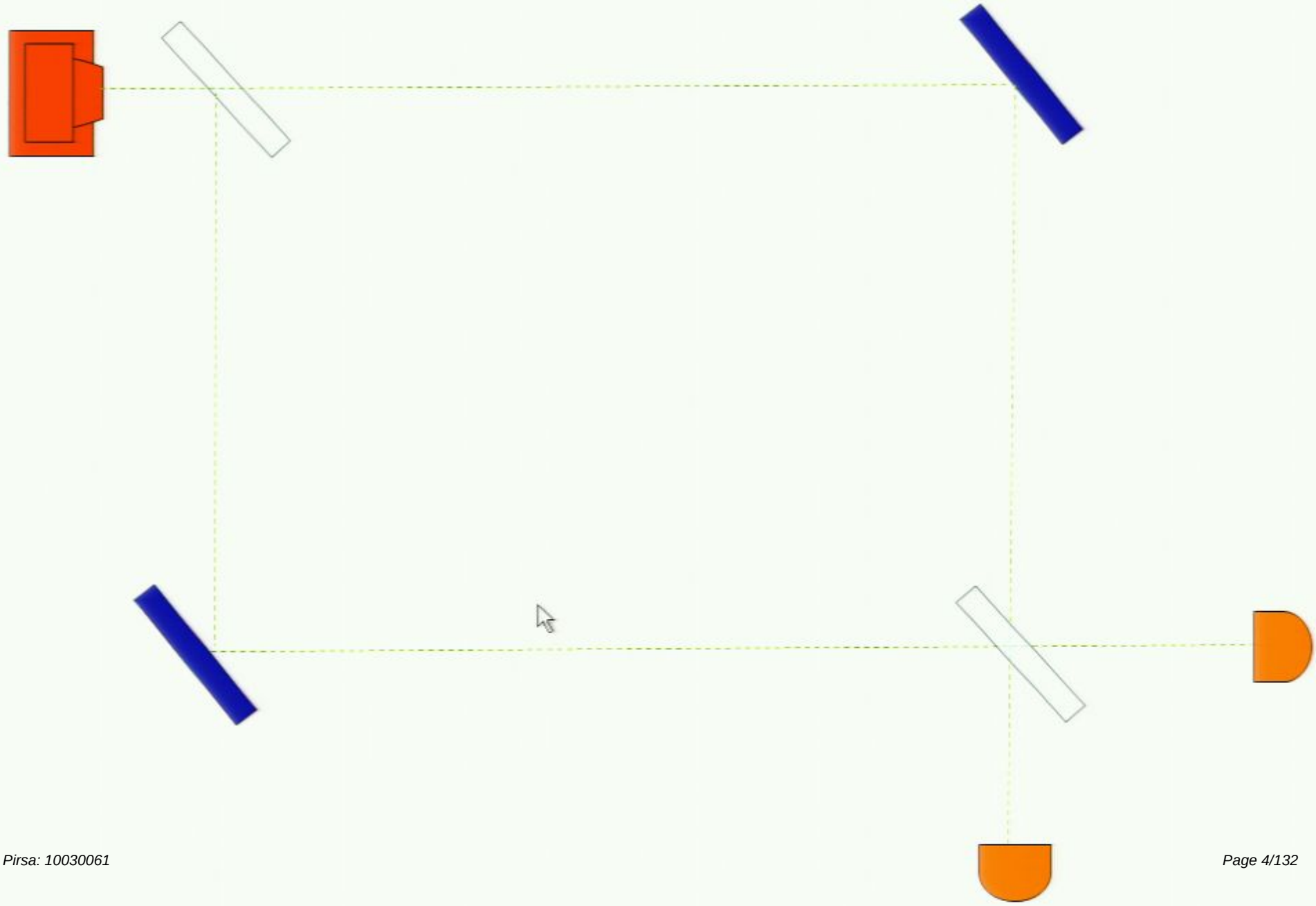
PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

16 March 2010

Where Is the Quantum Particle between Two Measurements?



Where is the photon when it is inside a Mach-Zehnder interferometer?



Interaction-free measurement

A. Elitzur and L. Vaidman
Found. Phys. **23**, 987 (1993) .

BOMB:

explodes when any particle "touches" it

interacts only through explosion

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HOW TO FIND THE BOMB WITHOUT EXPLODING IT?

Interaction-free measurement

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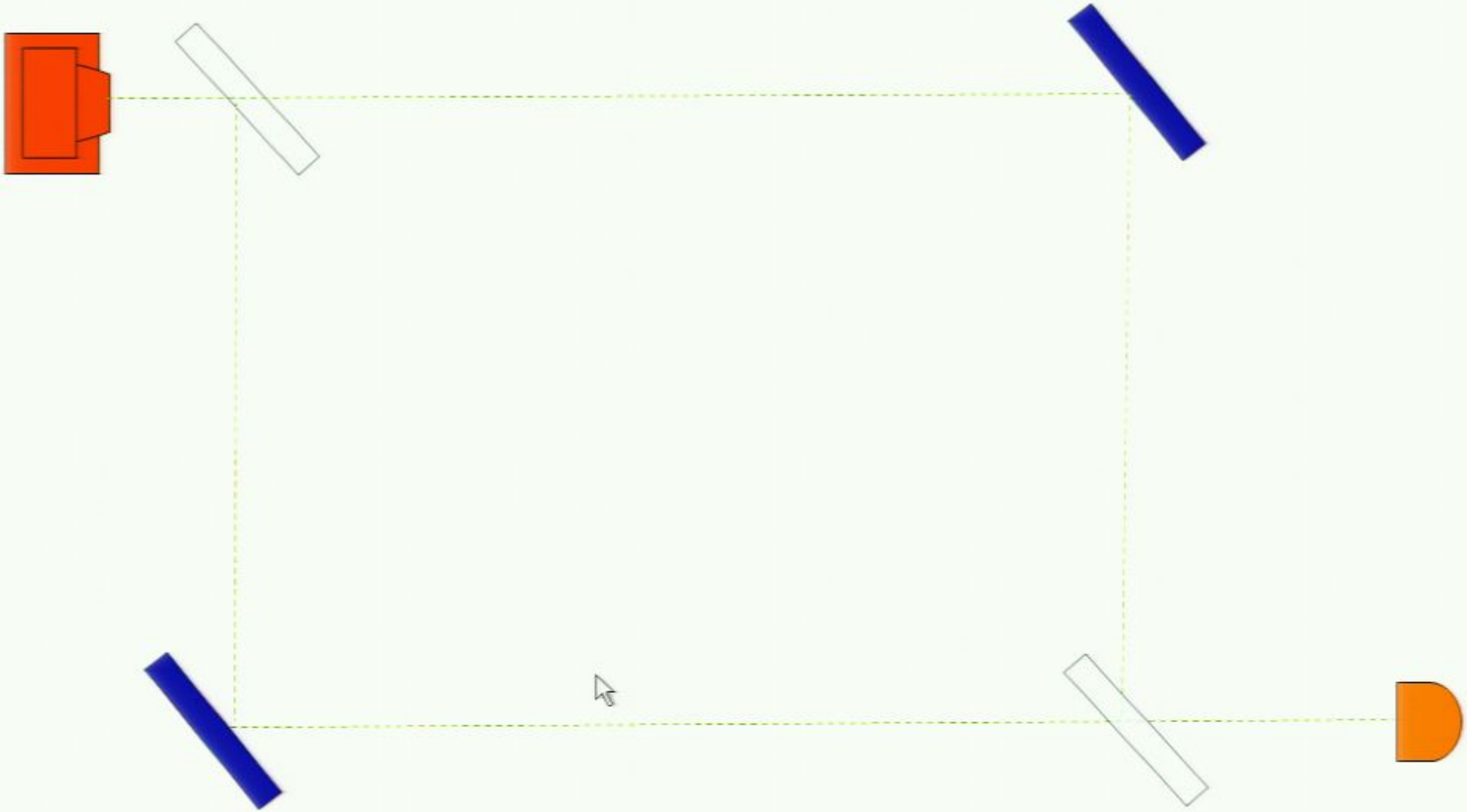

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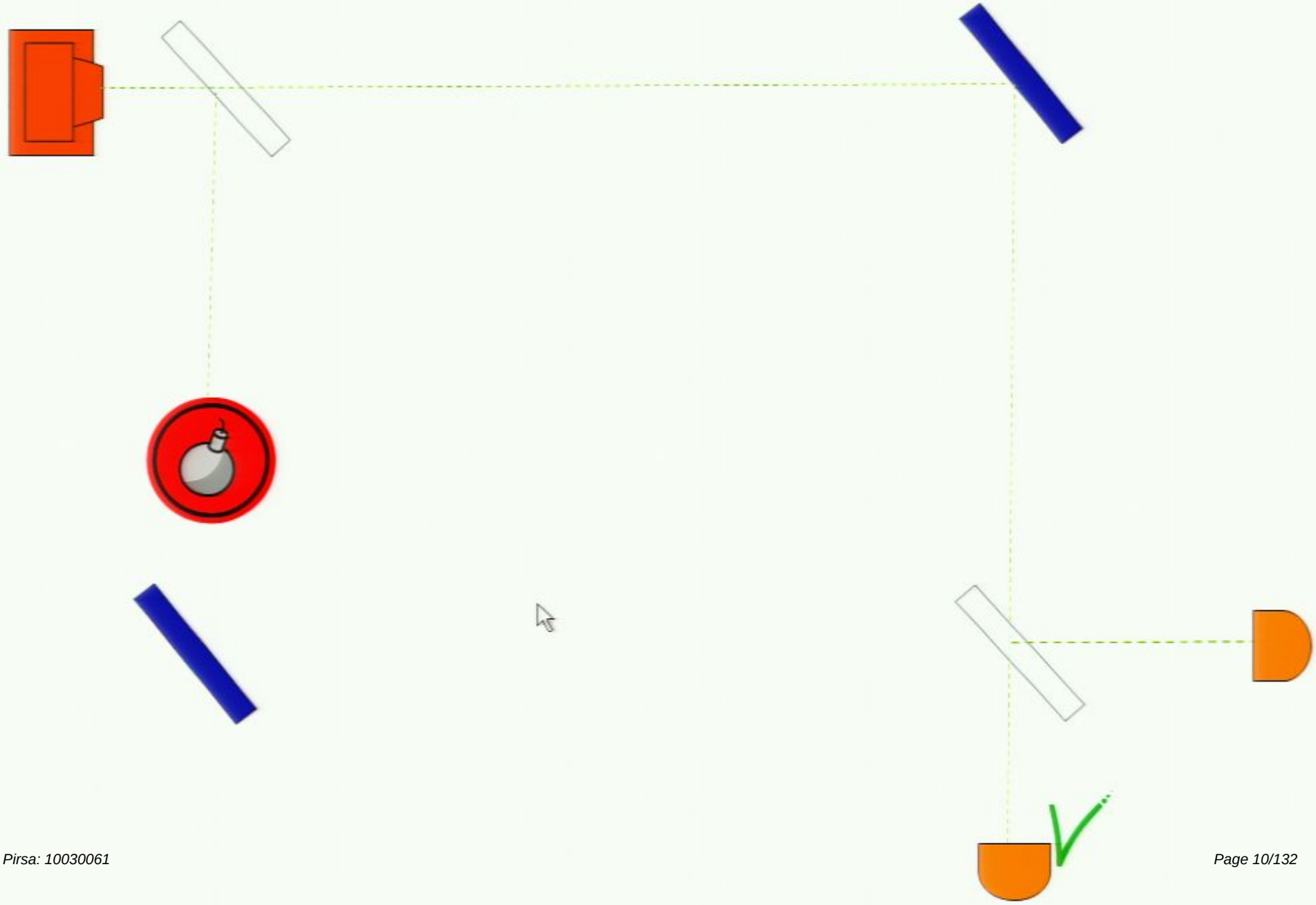

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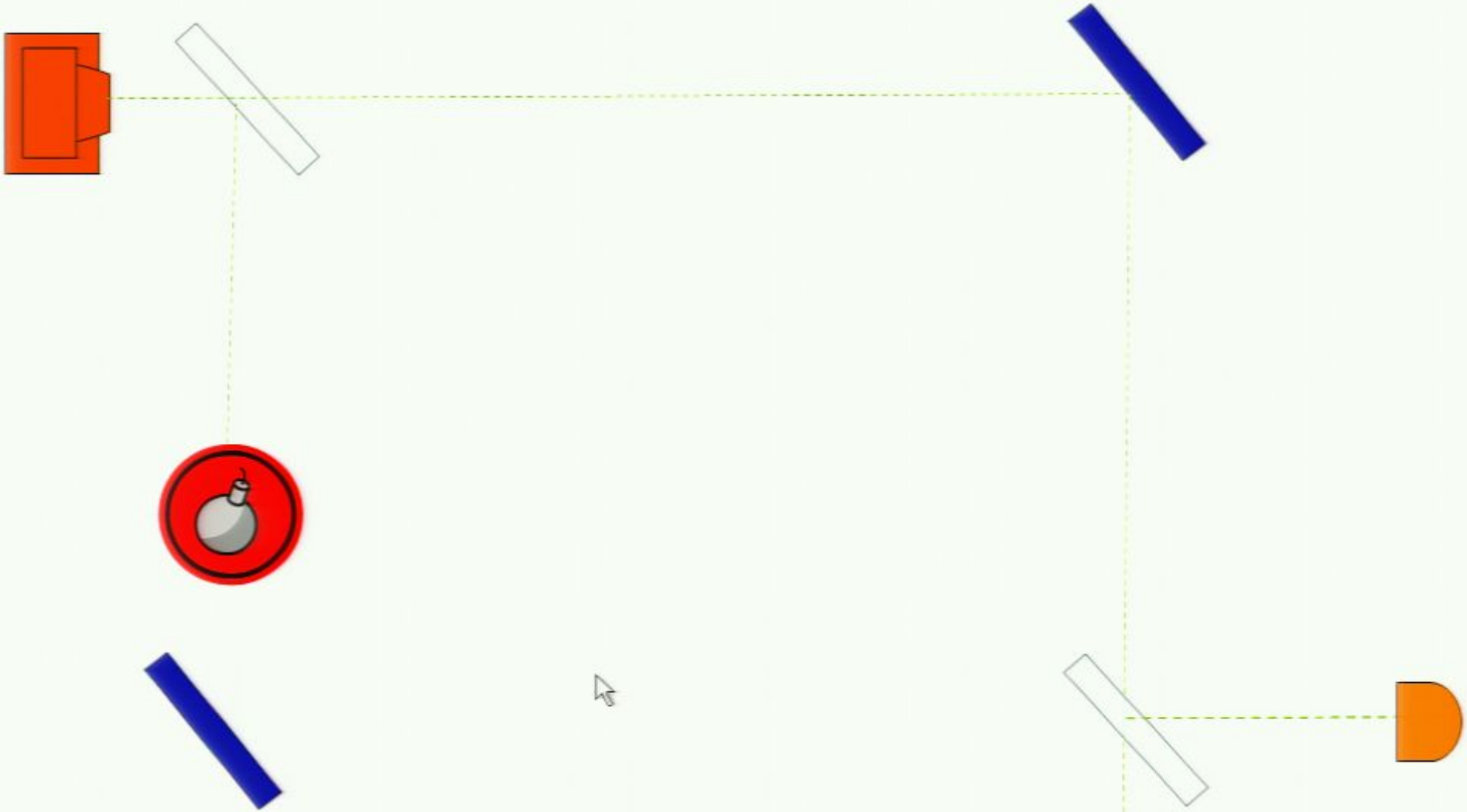
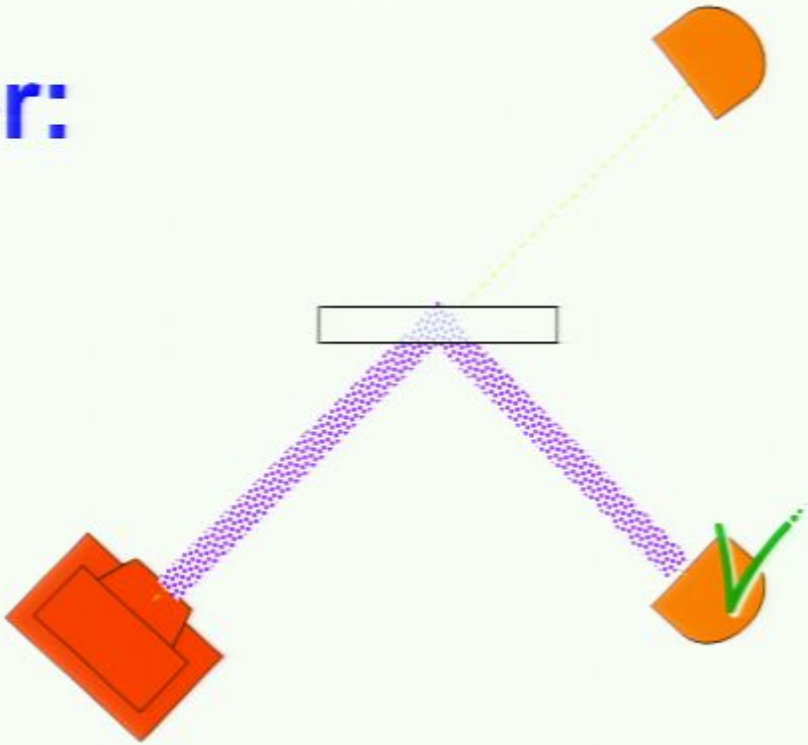


Did photon touched the bomb?

Wheeler:

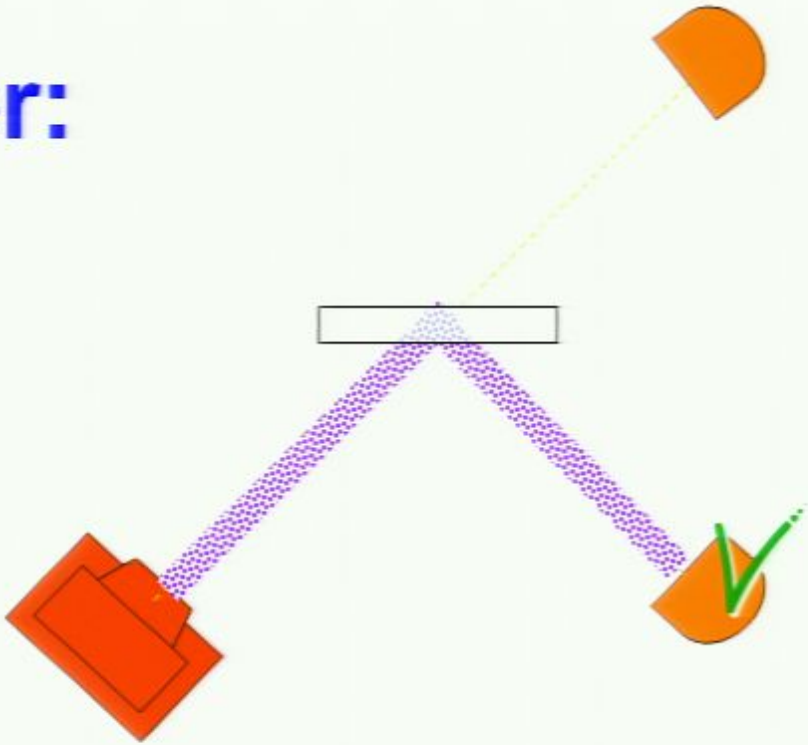


The present choice of observation influences what we say about the "past" of the photon; it is undefined and undefinable without the observation.

The "past" and the "Delayed Choice" Double-Slit Experiment

J.A. Wheeler 1978

Wheeler:



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No phenomenon is a phenomenon until it is an observed phenomenon.

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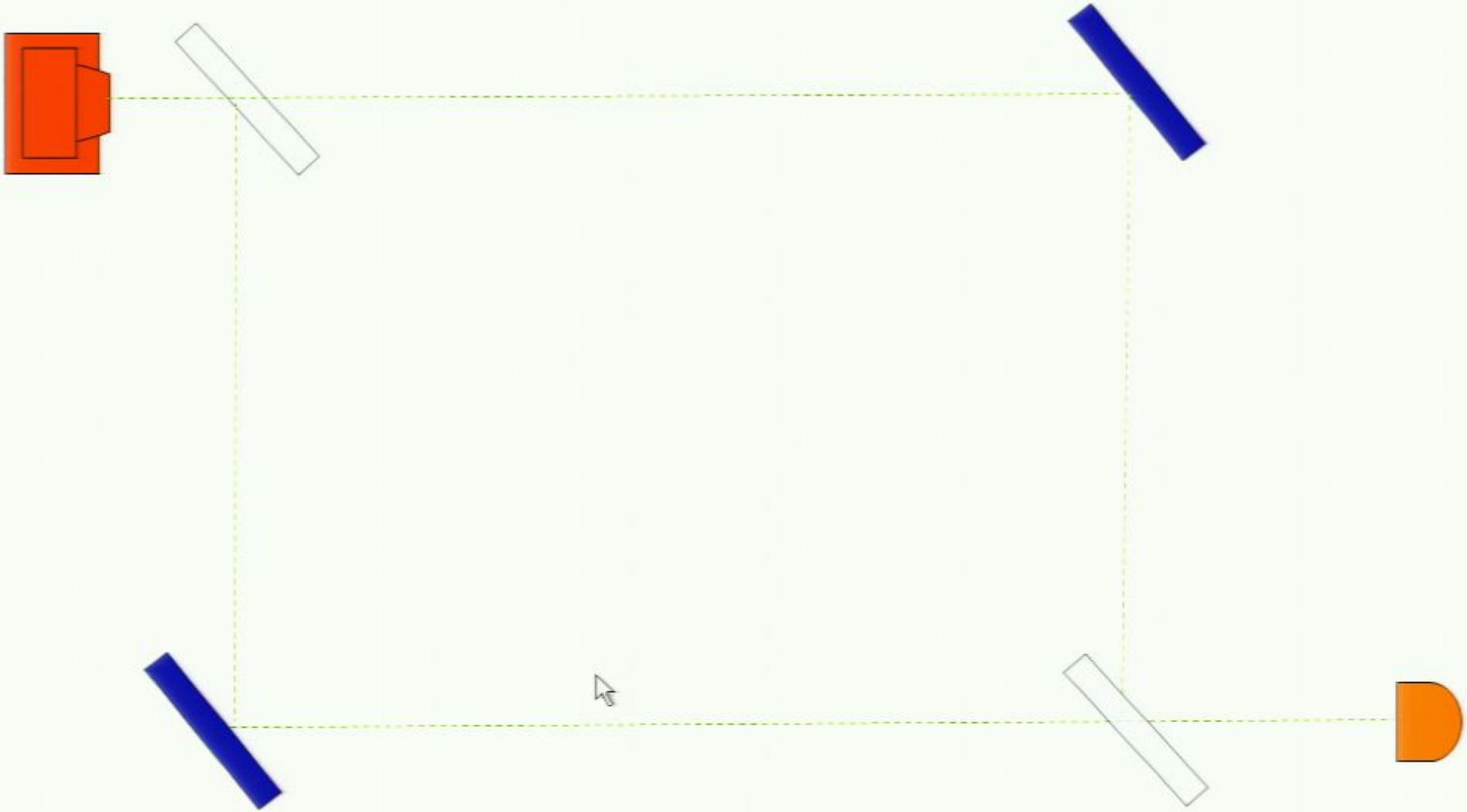
Wheeler delayed choice experiment



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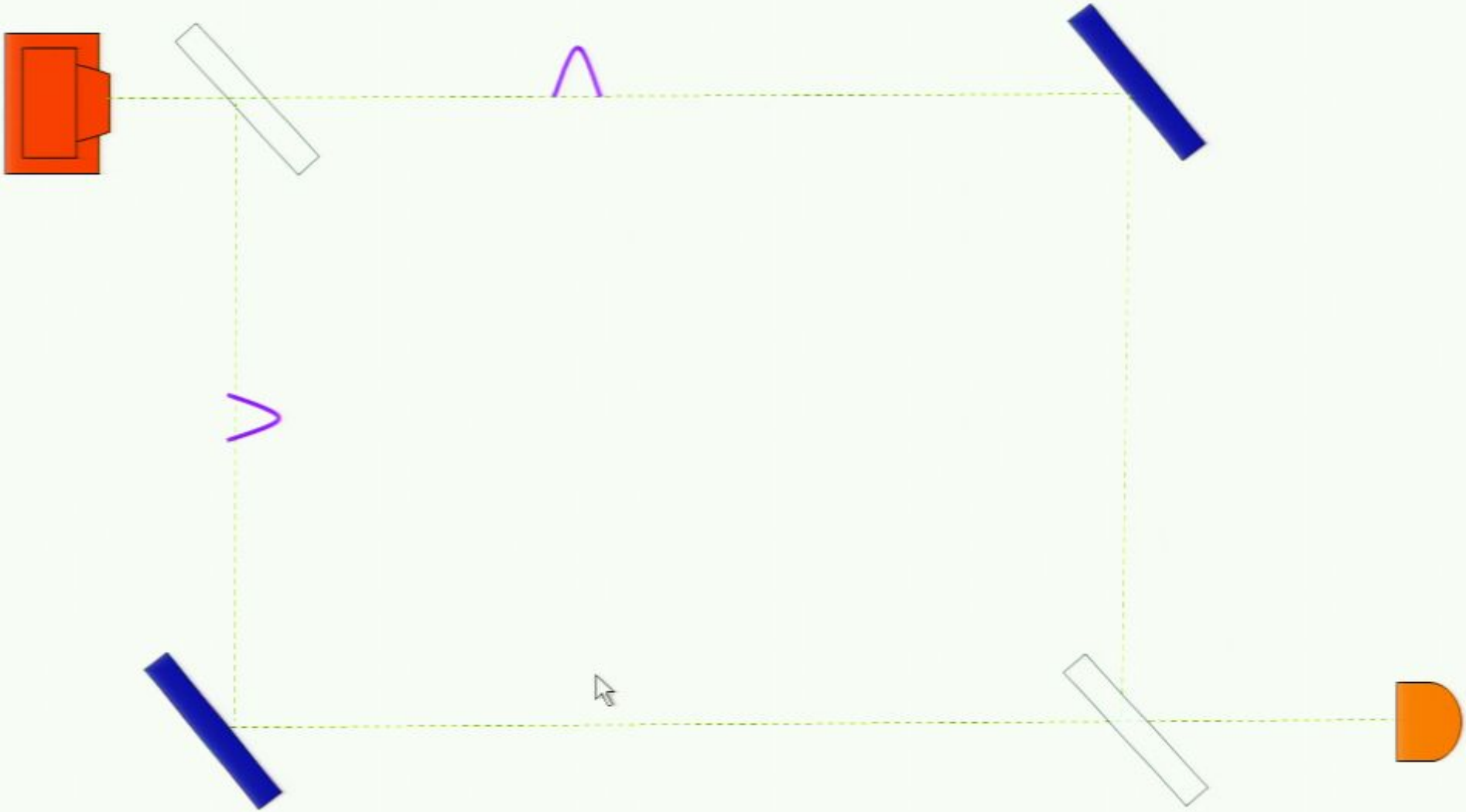

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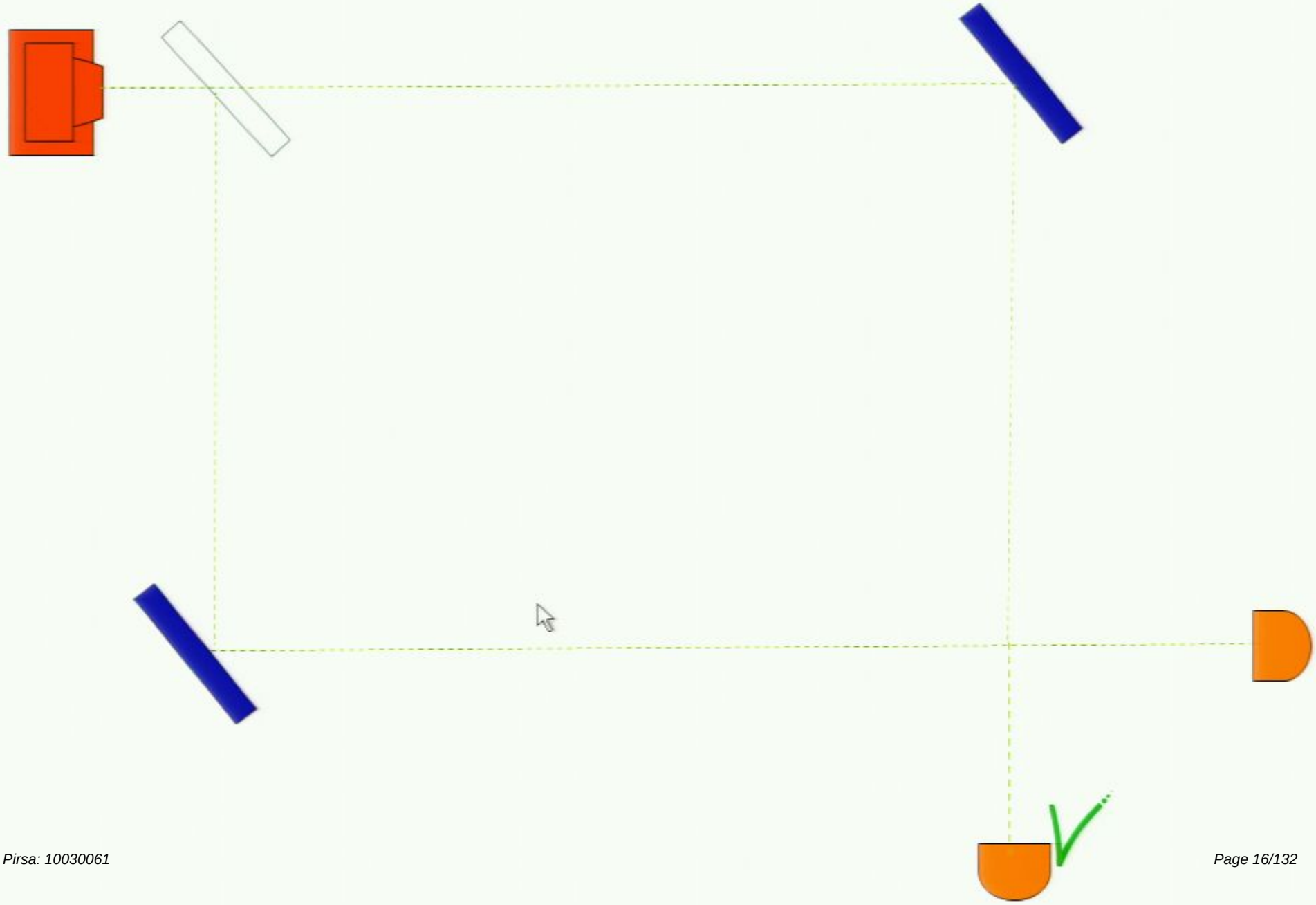

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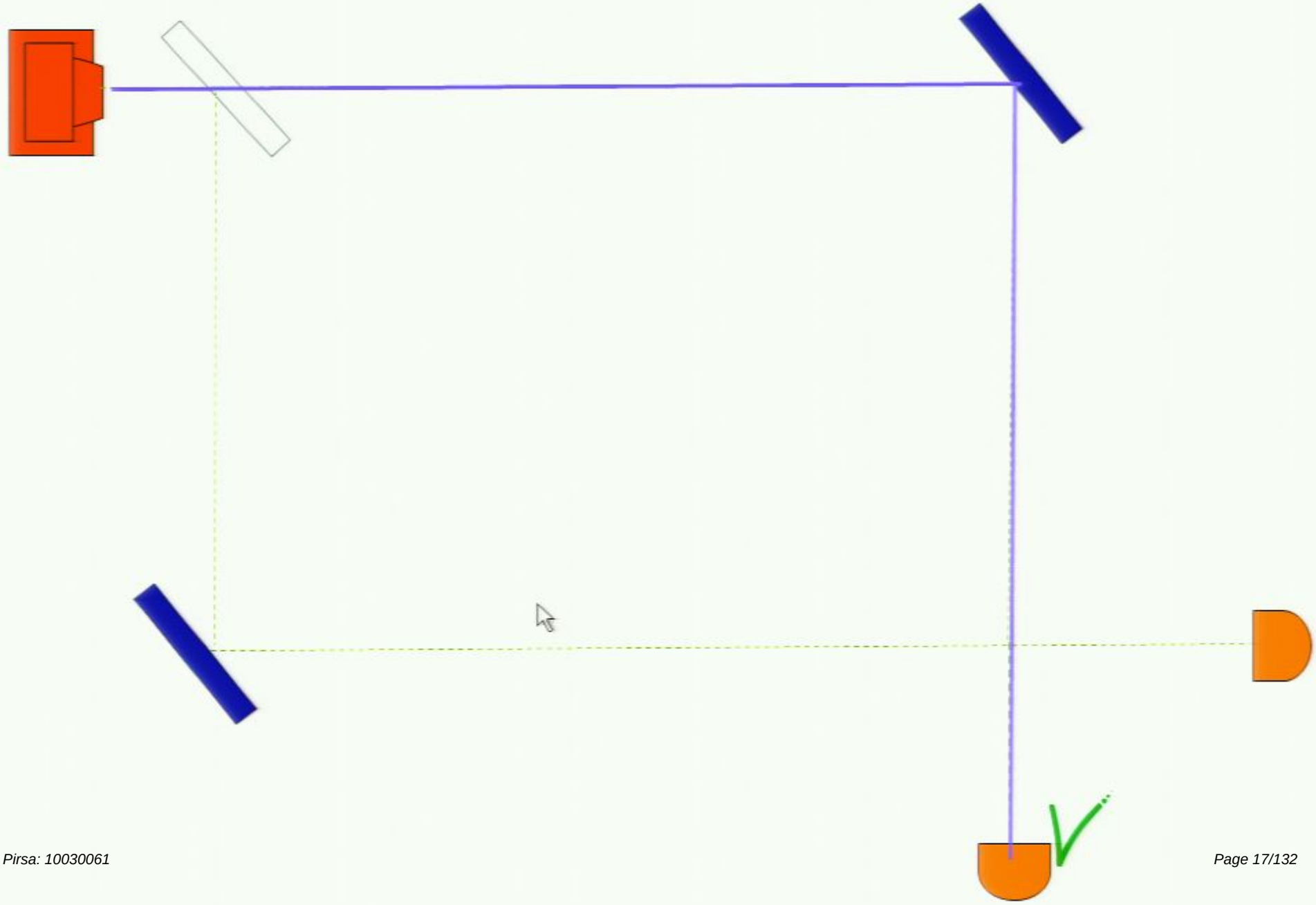

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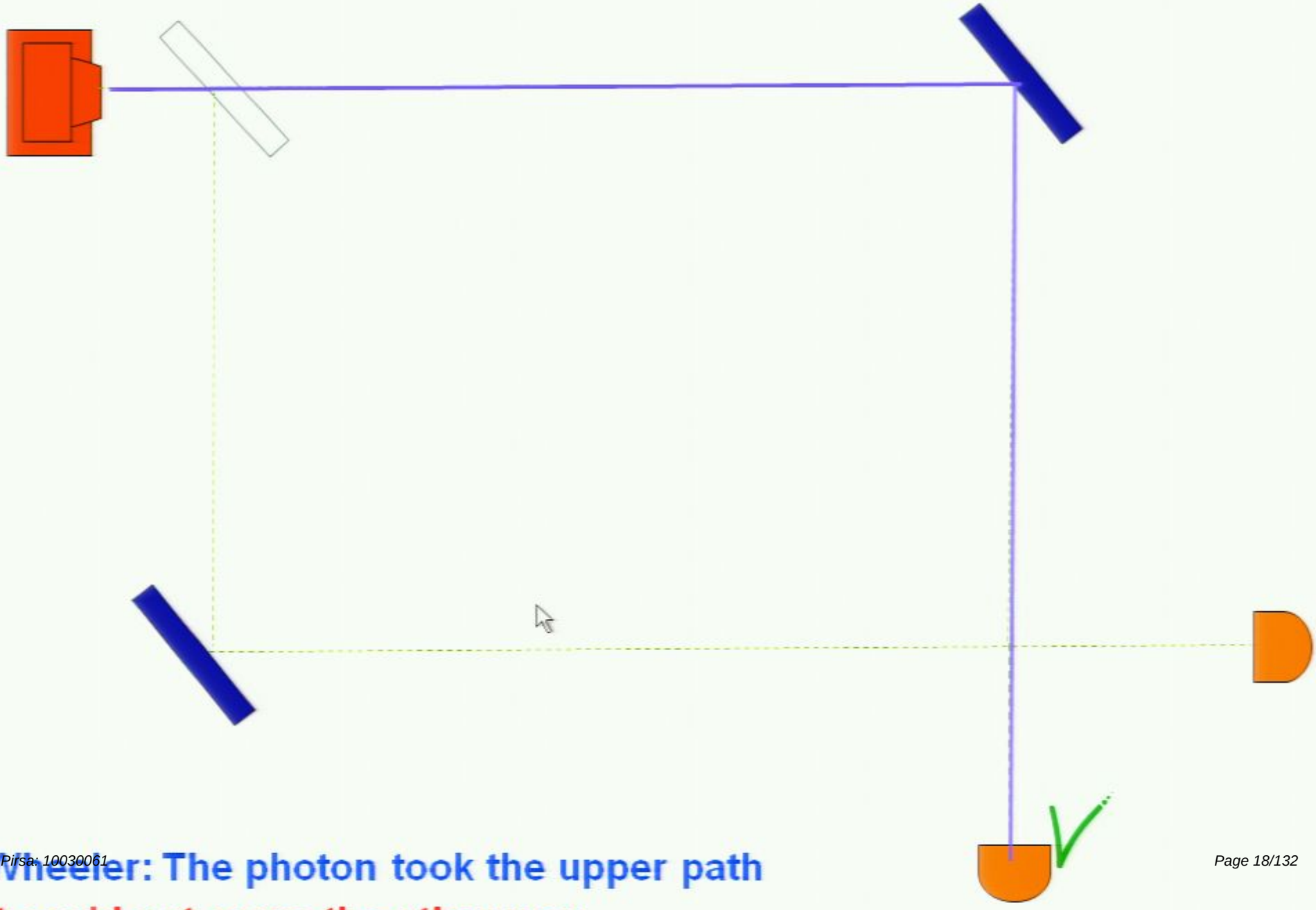
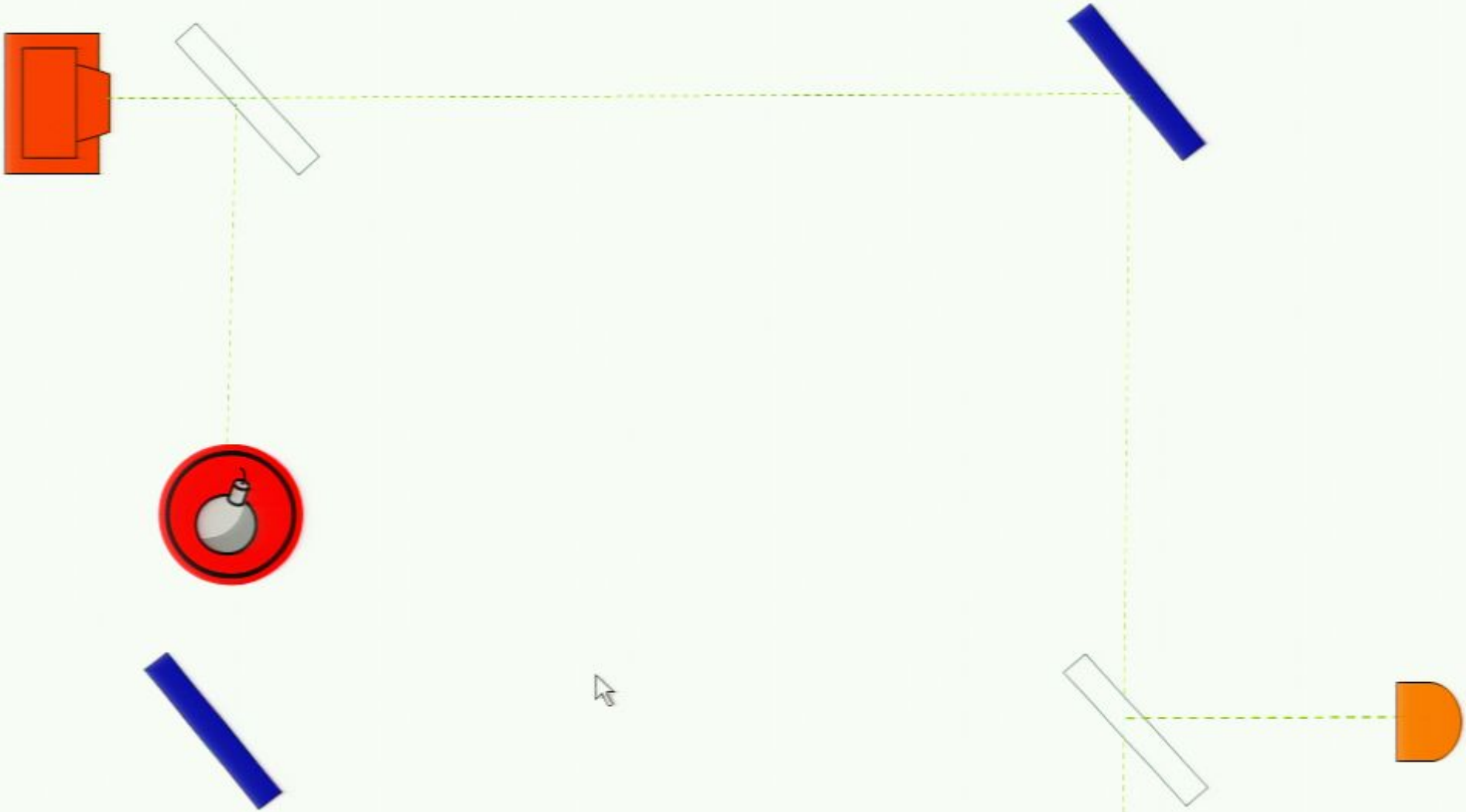


Wheeler: The photon took the upper path

Interaction-free measurement



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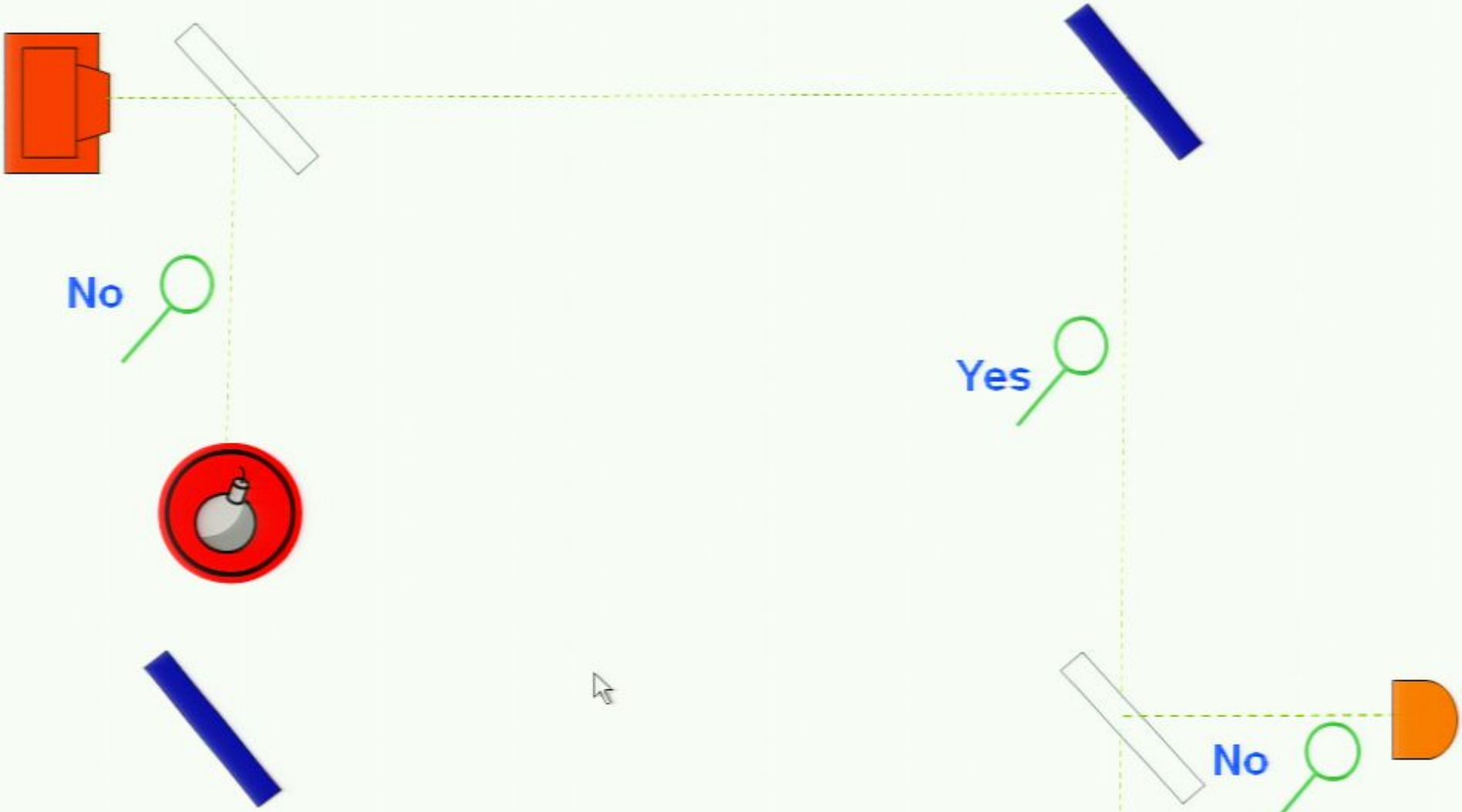

Did photon touched the bomb?

Operational meaning:

- Nondemolition measurements show NO!

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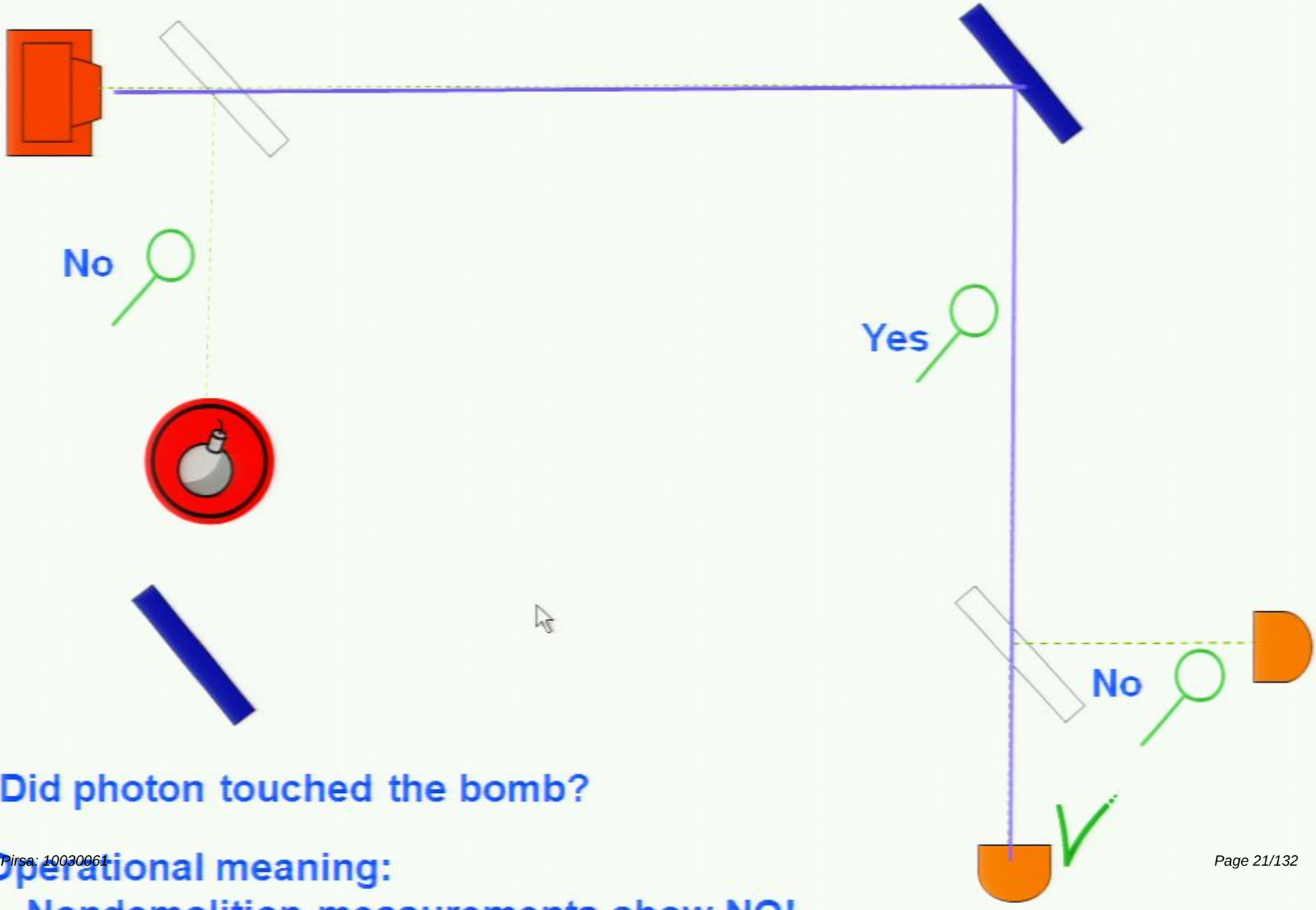

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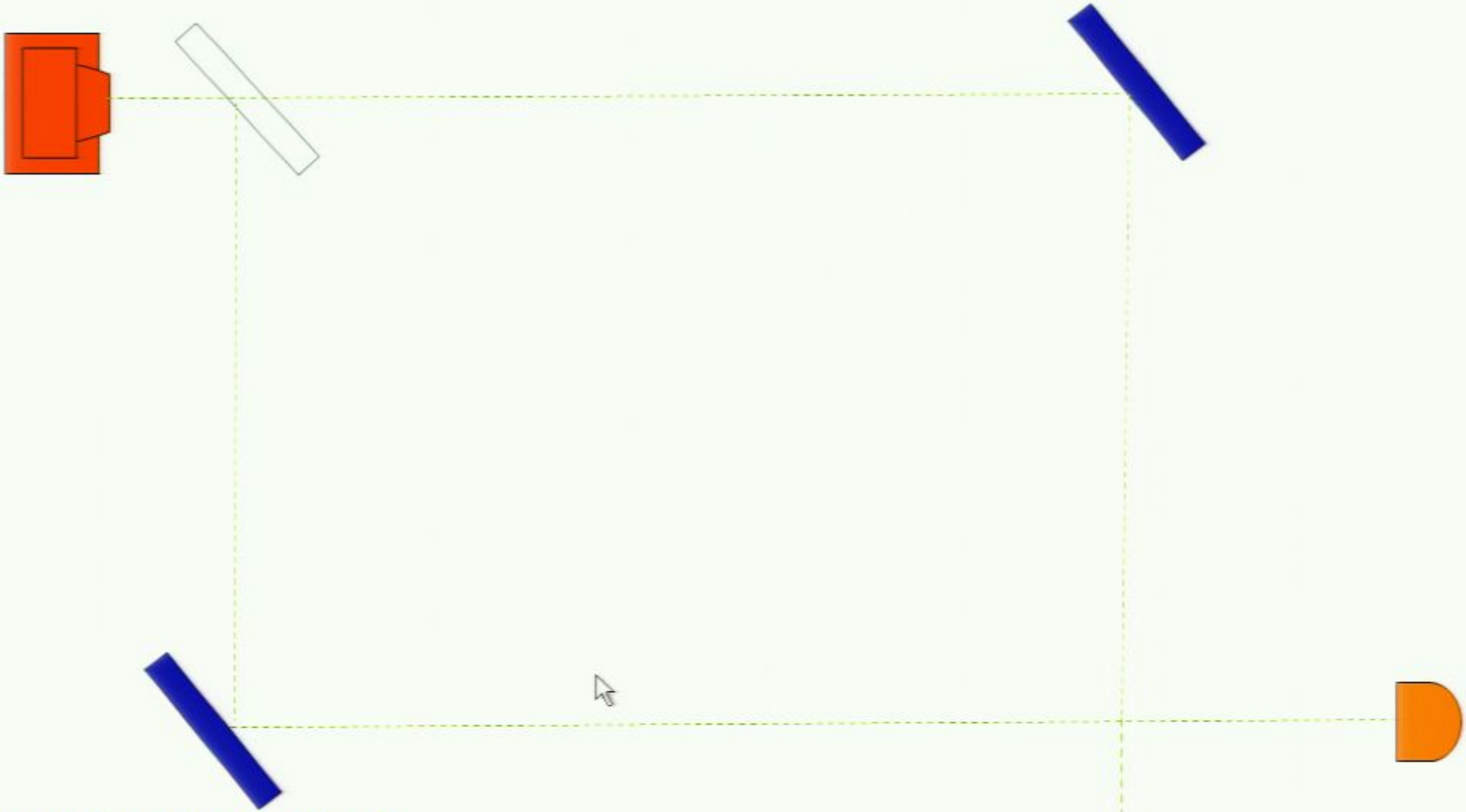

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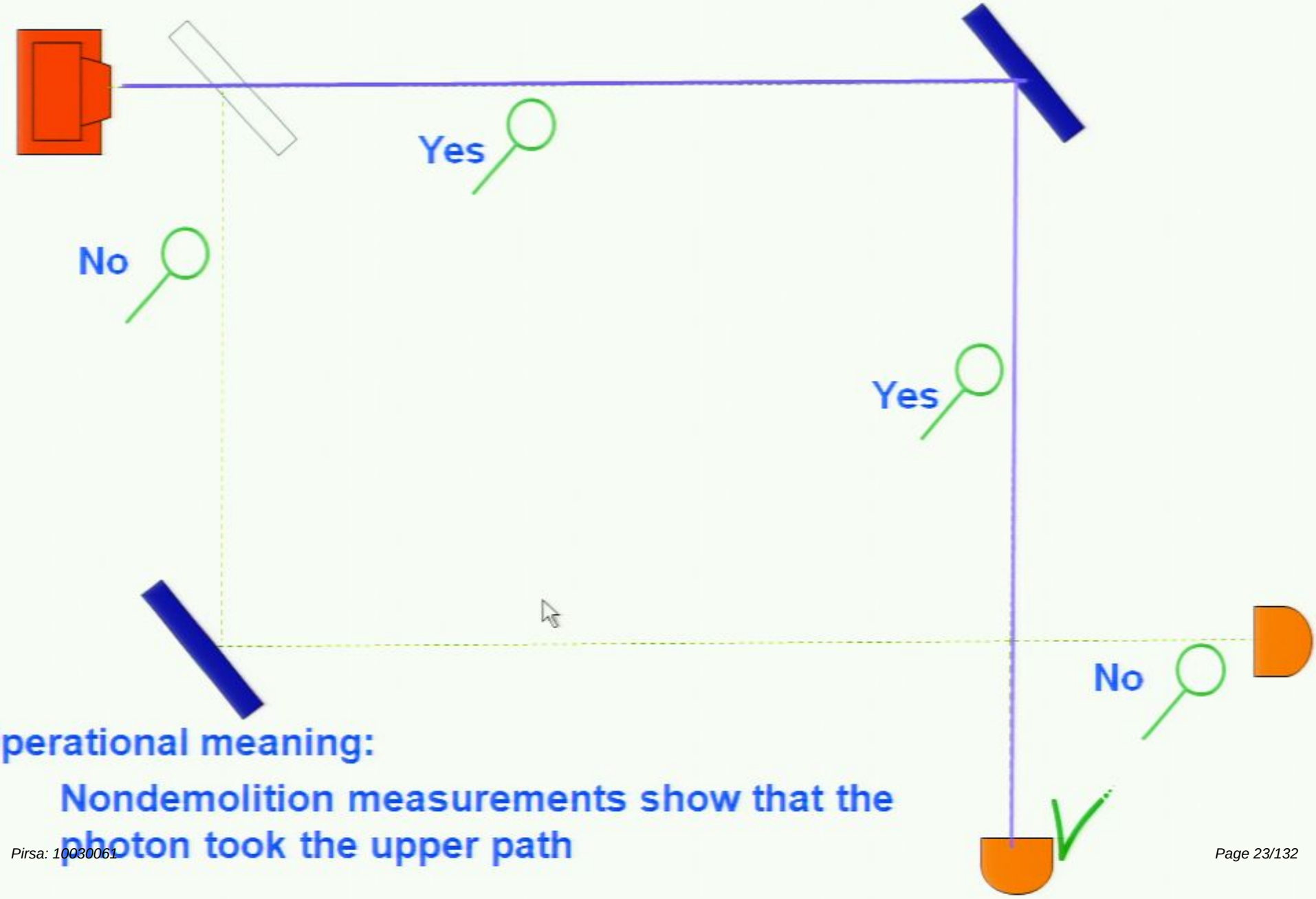

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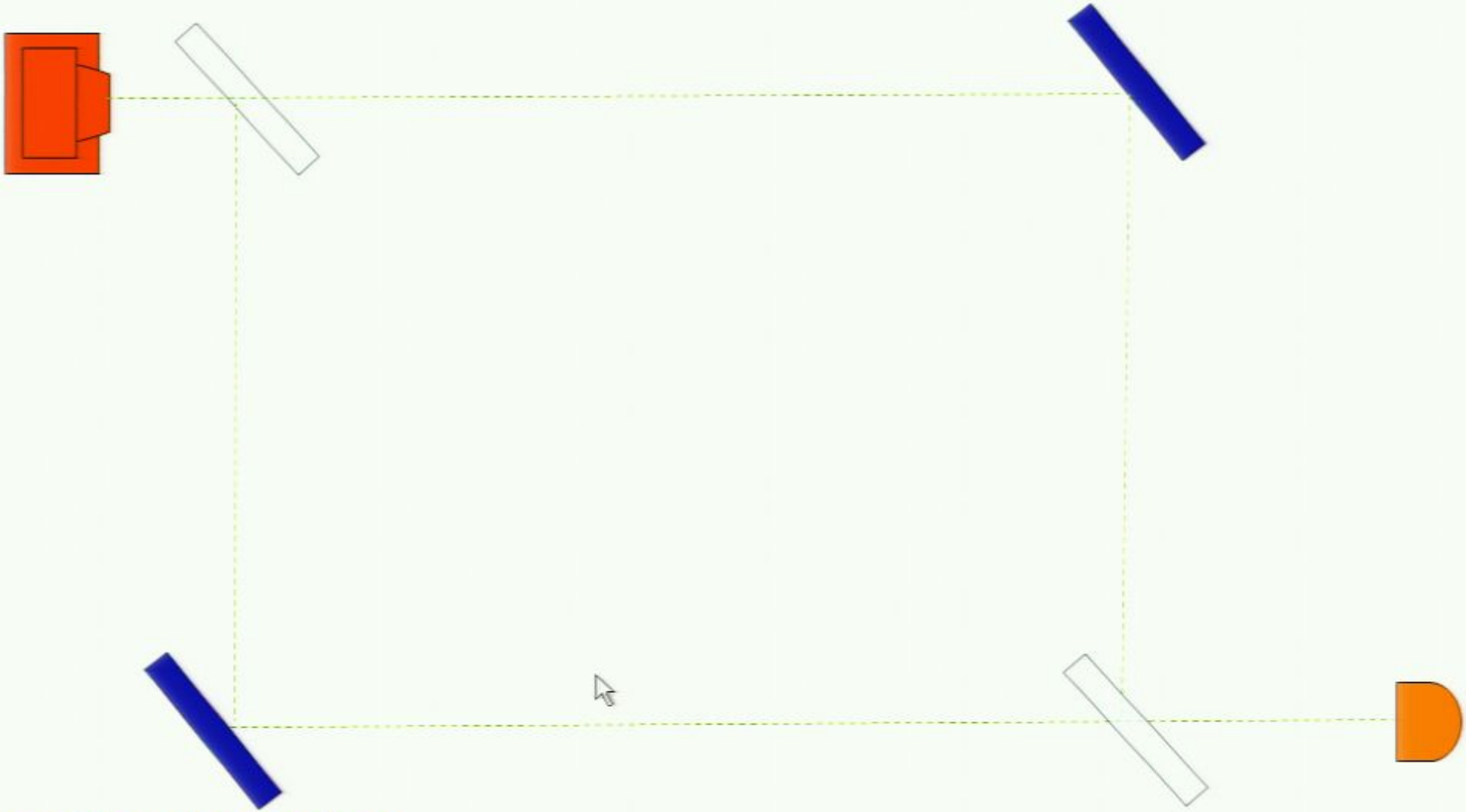
Where is the photon when it is inside a Mach-Zehnder interferometer?



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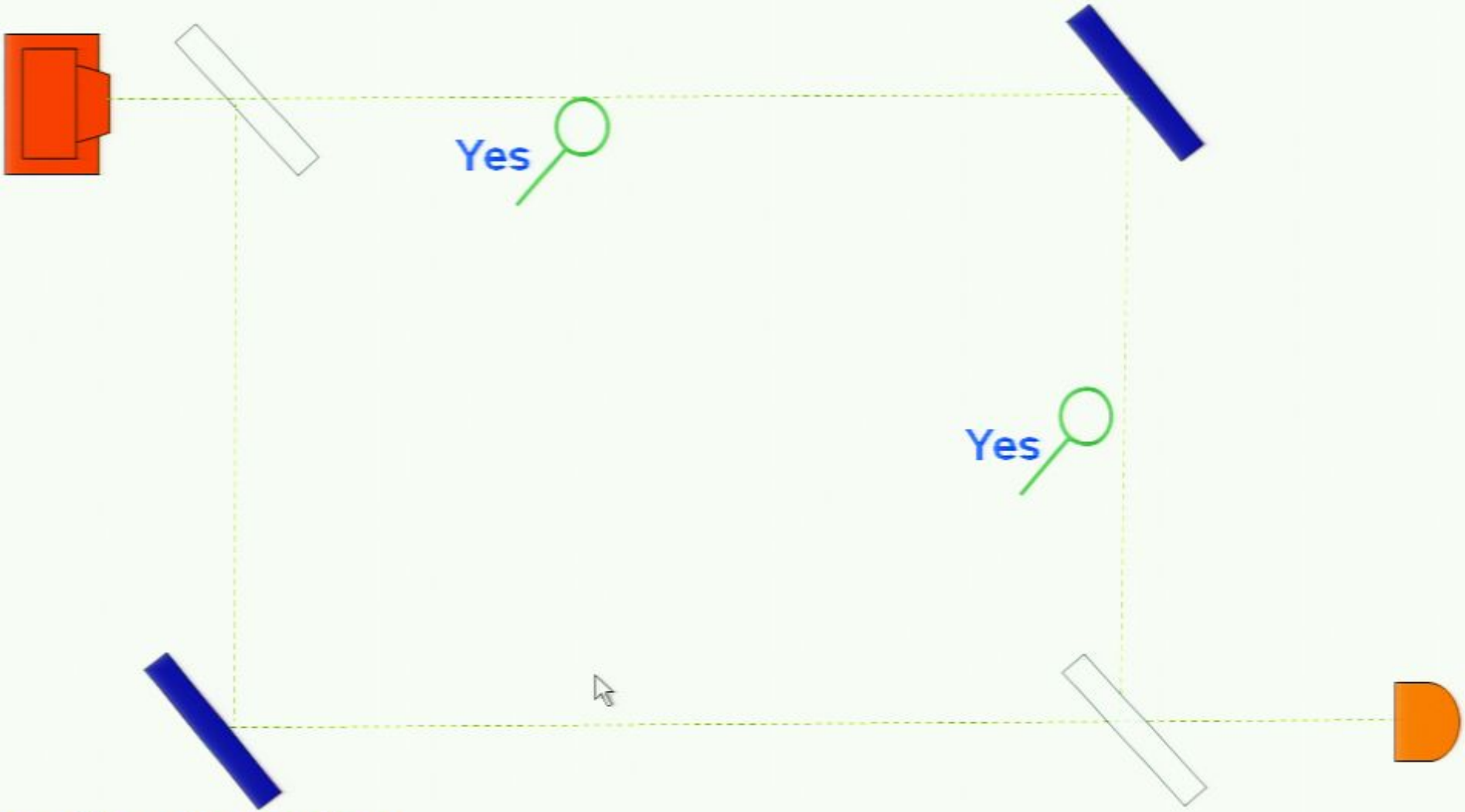

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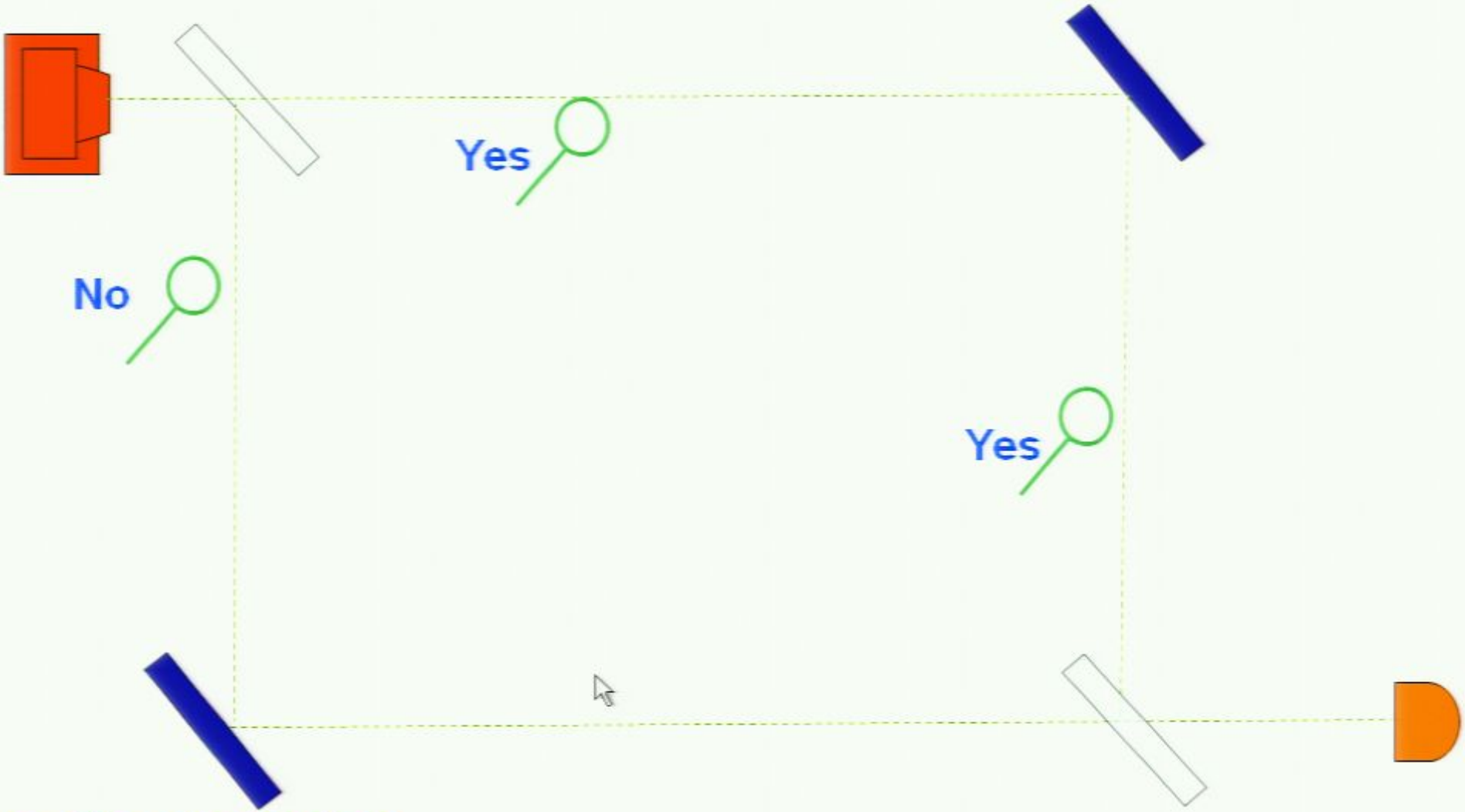

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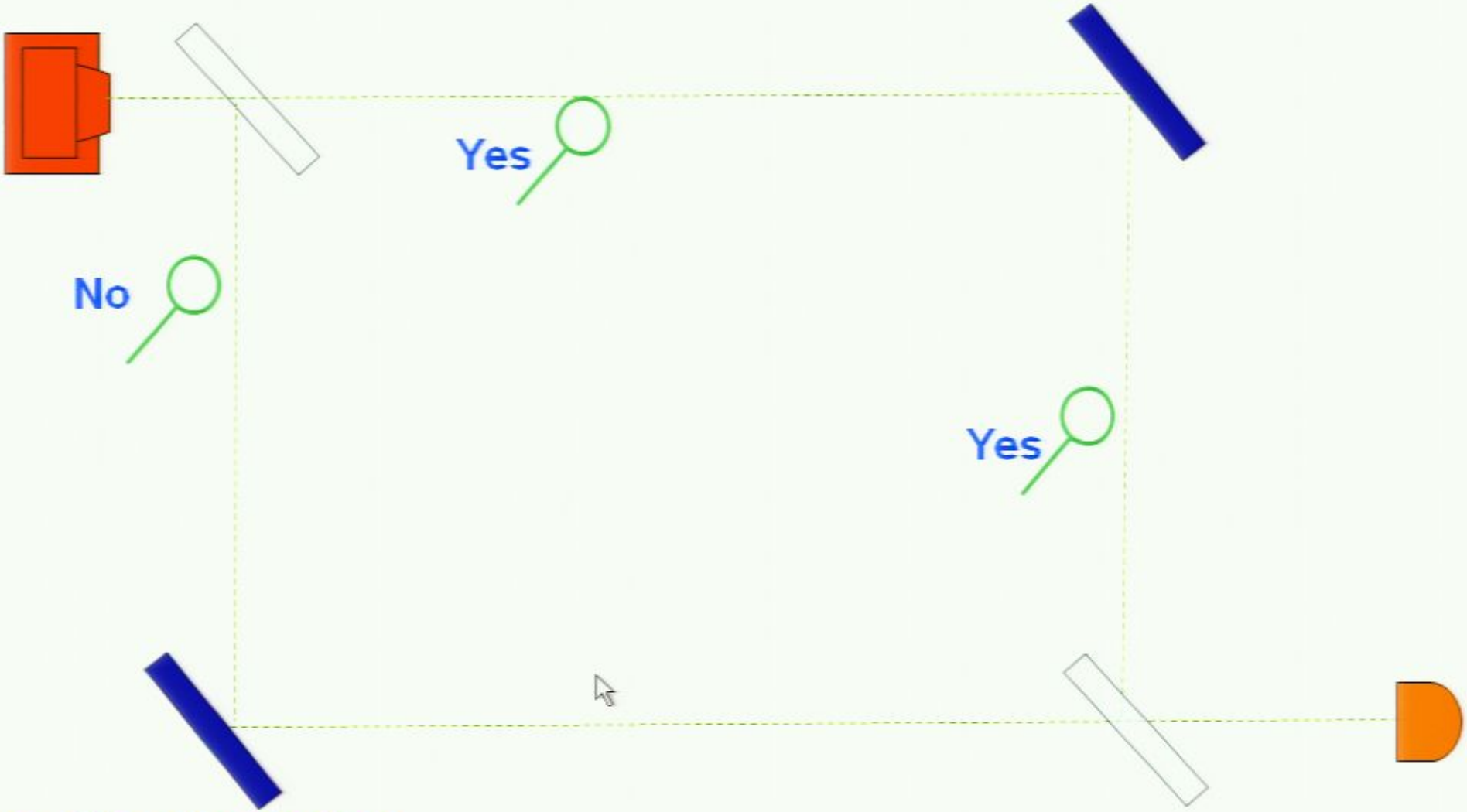

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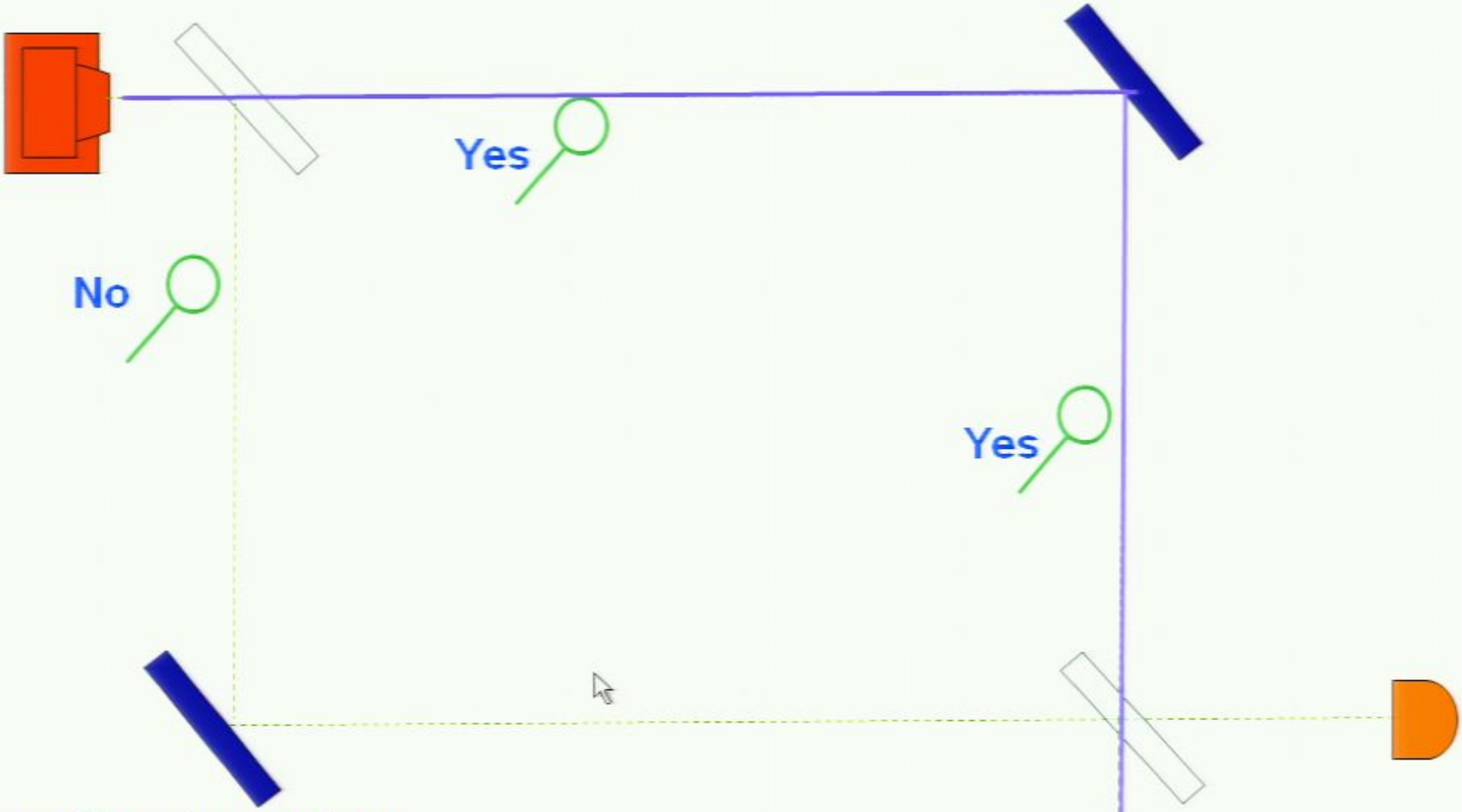

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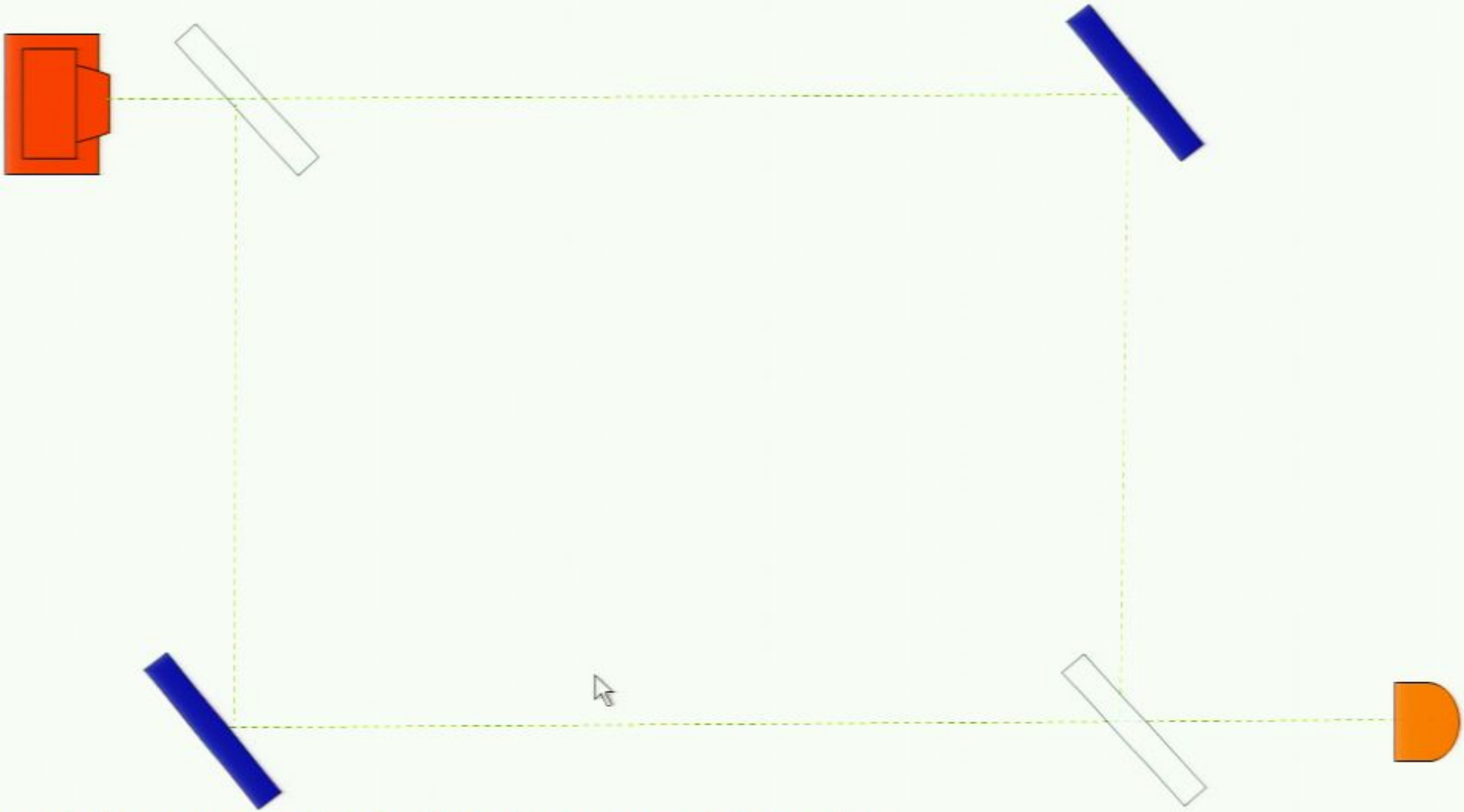

Operational meaning: **Weak measurements**
(no disturbance at the limit)

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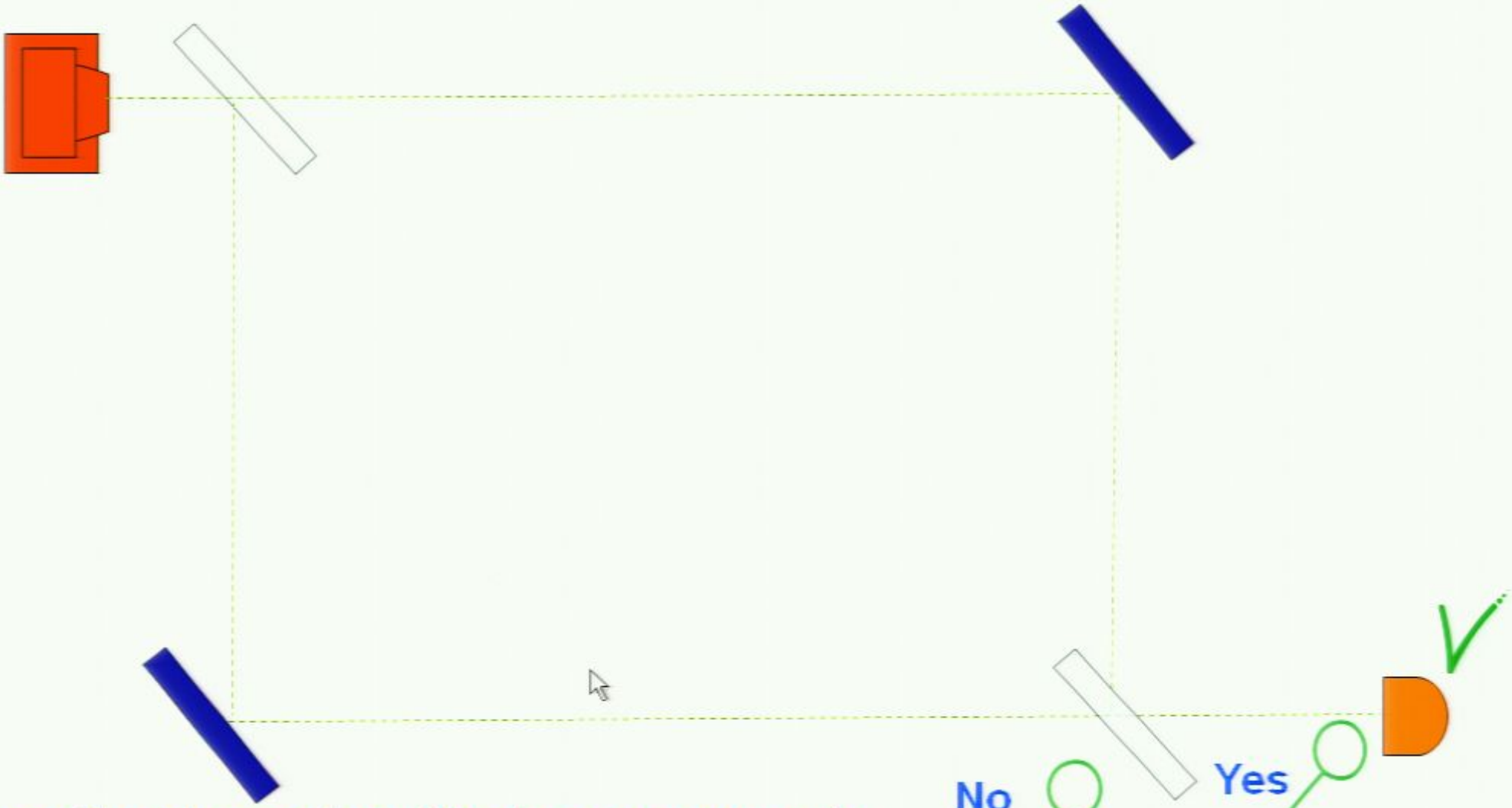

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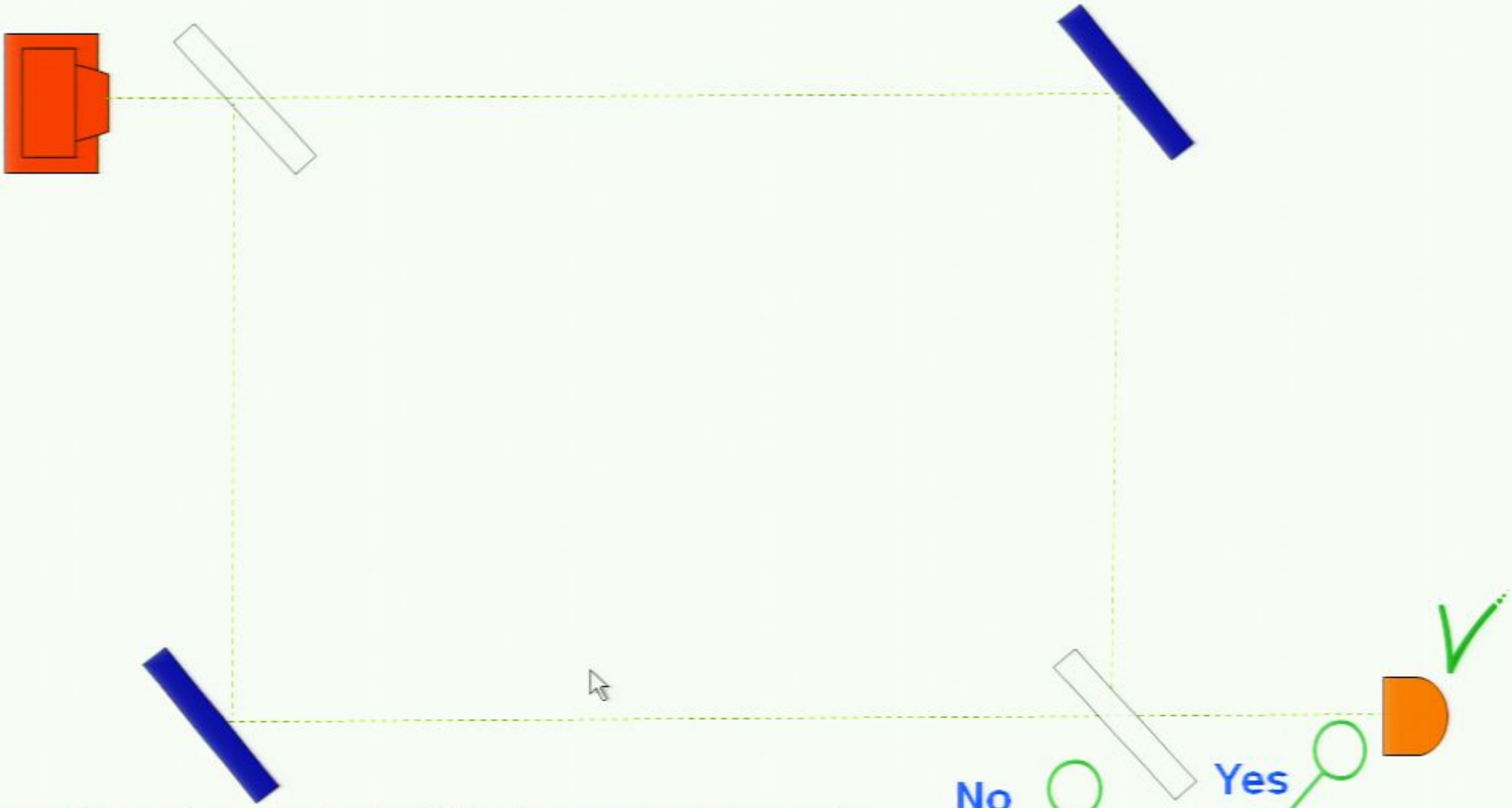

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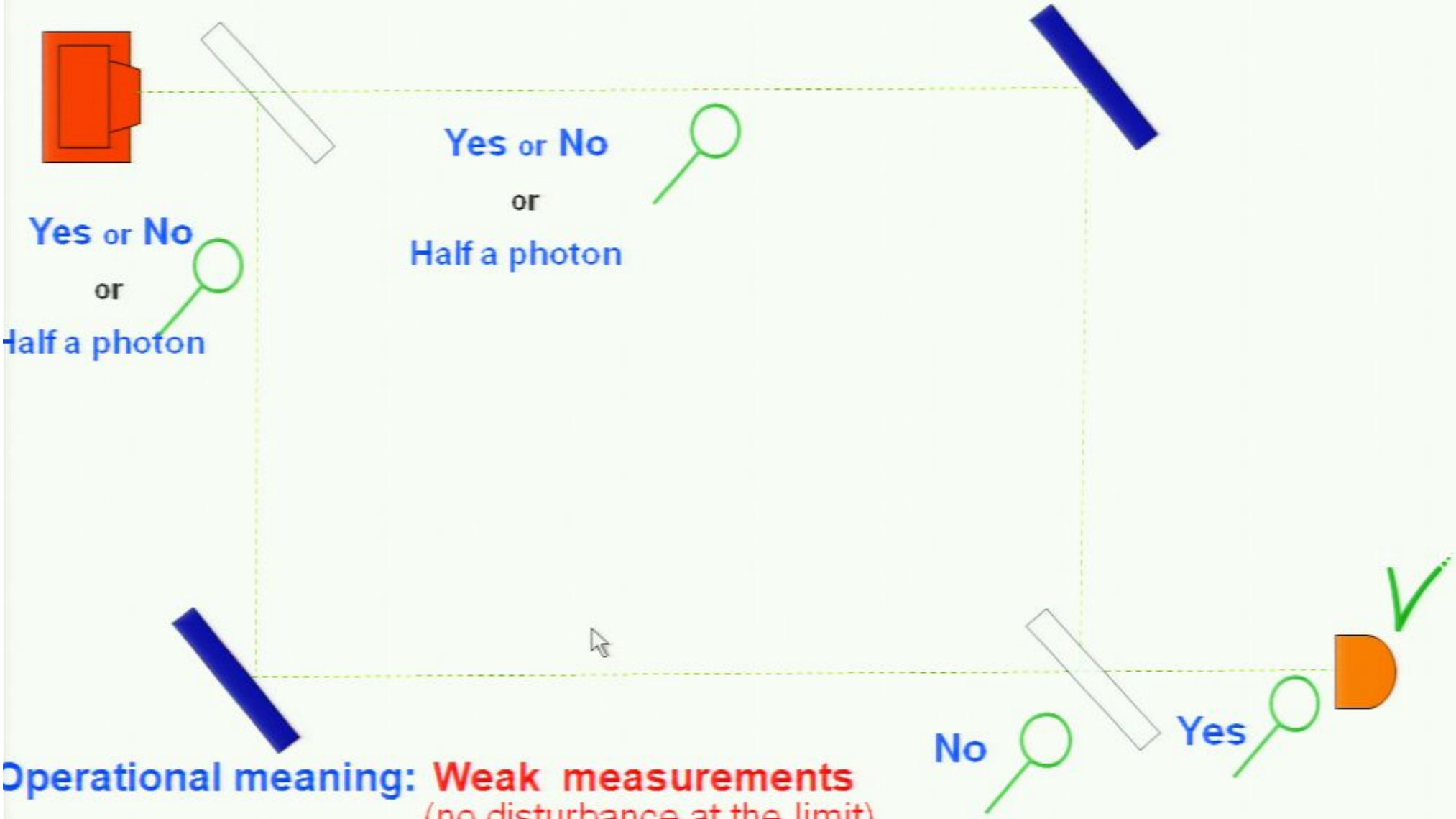

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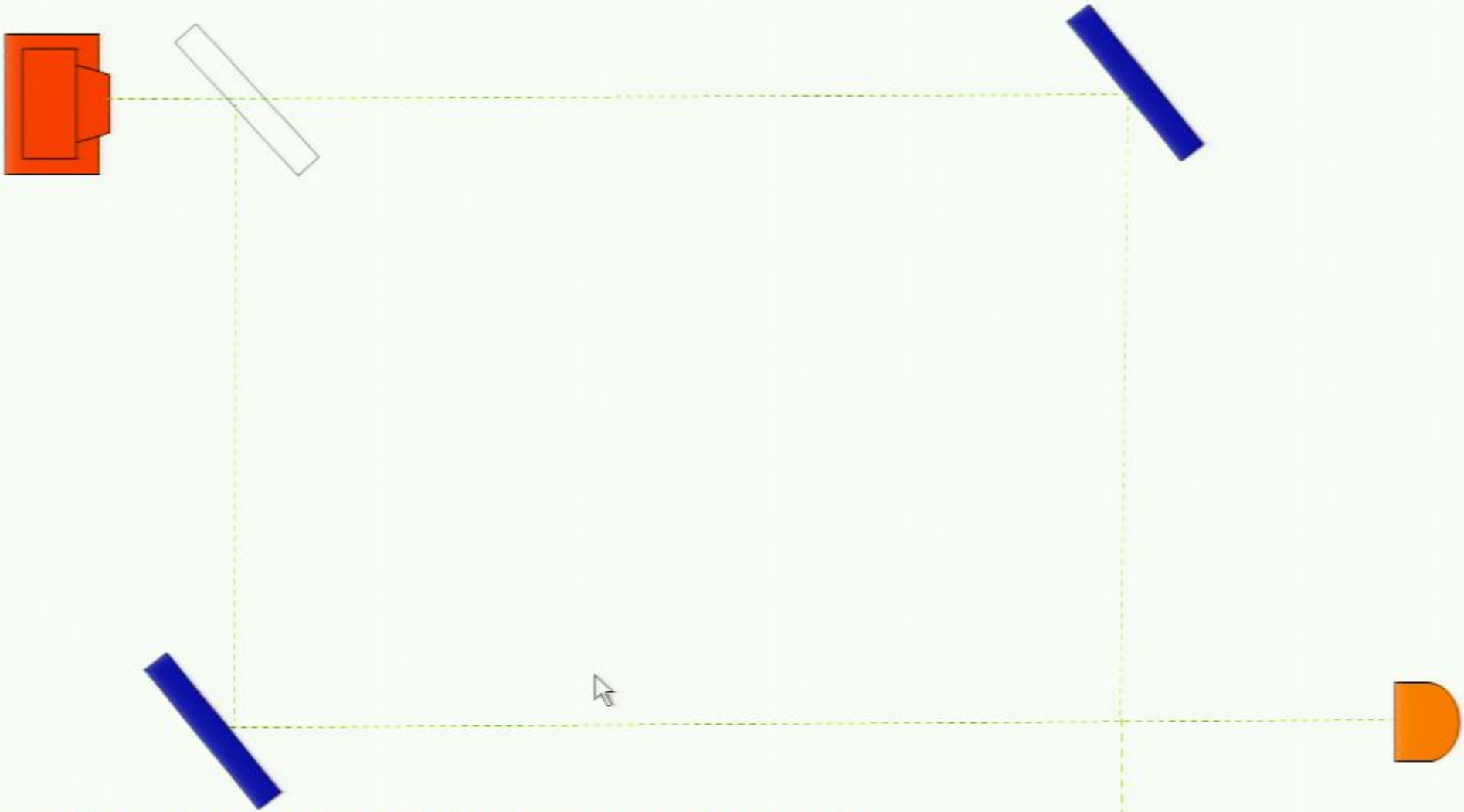
"Half a photon" or half the times the photon passes each path

Wheeler delayed choice experiment



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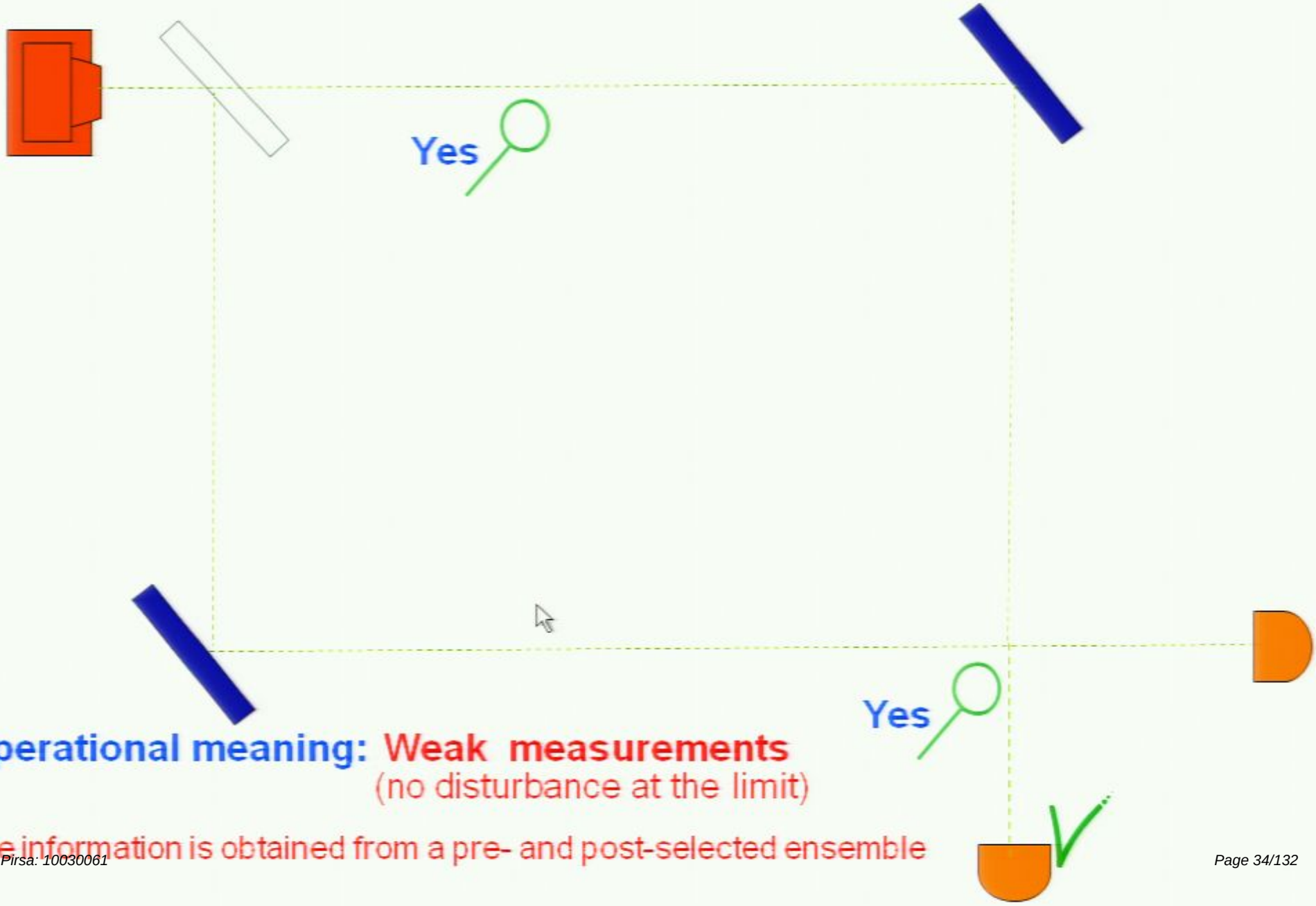

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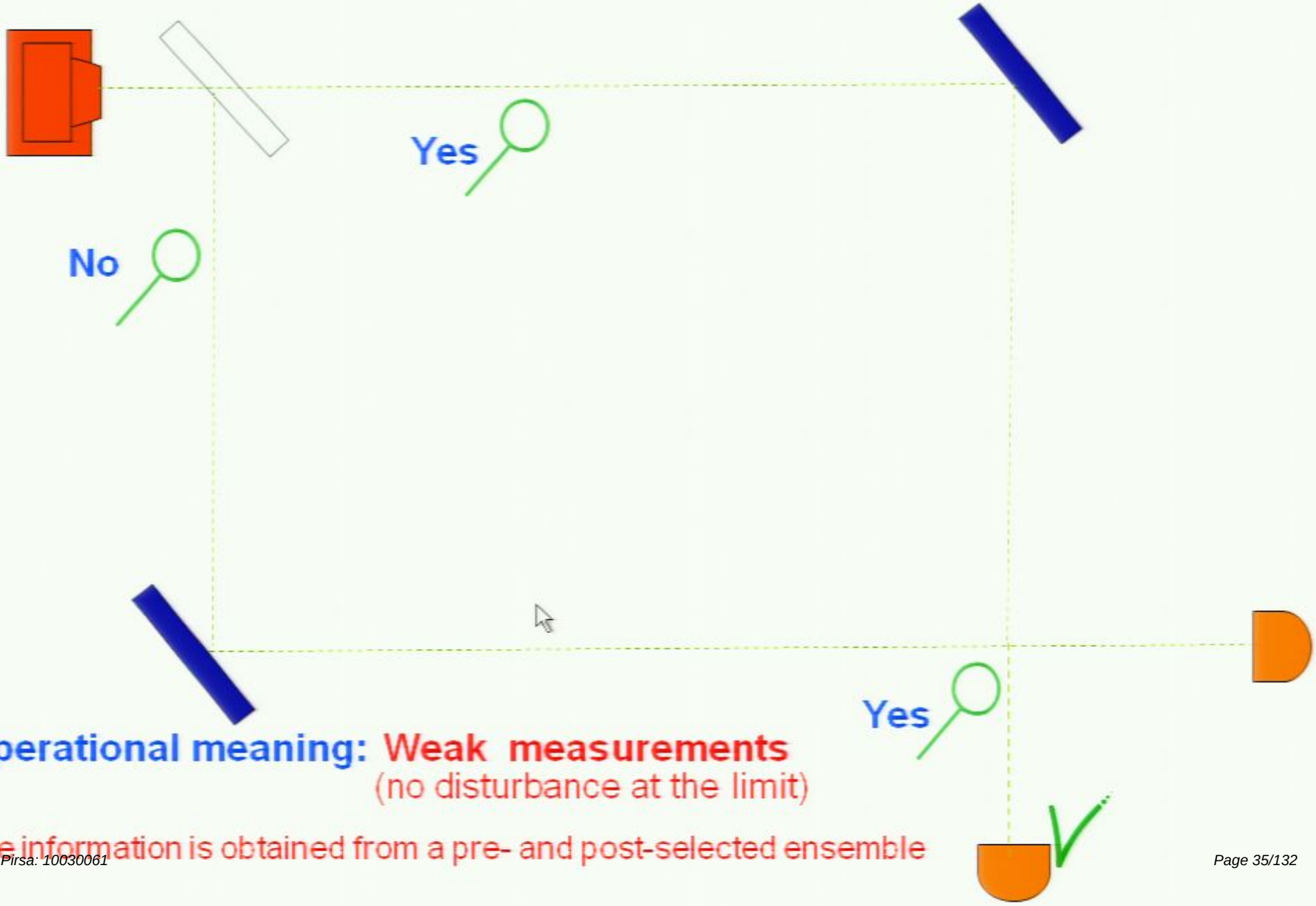

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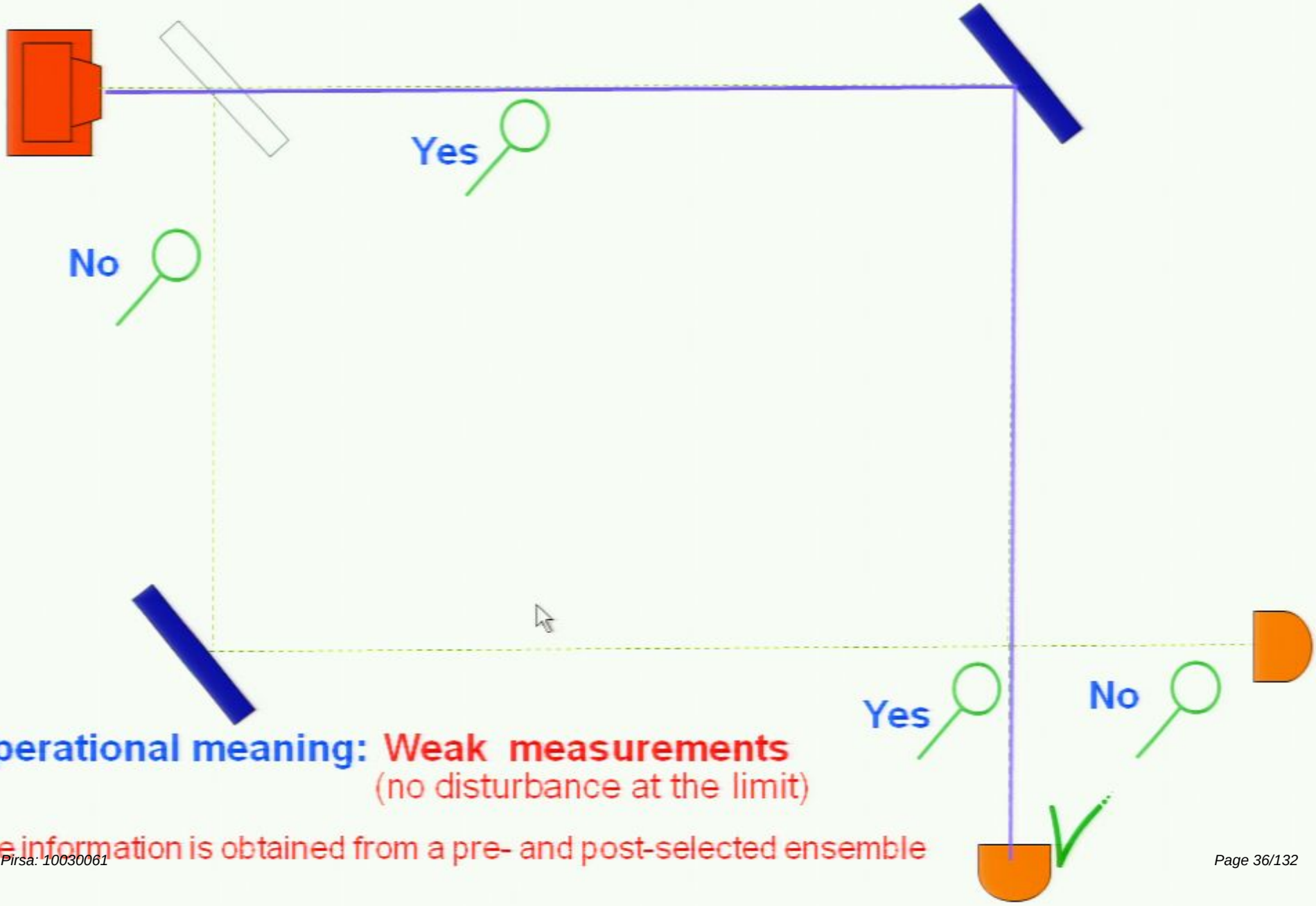

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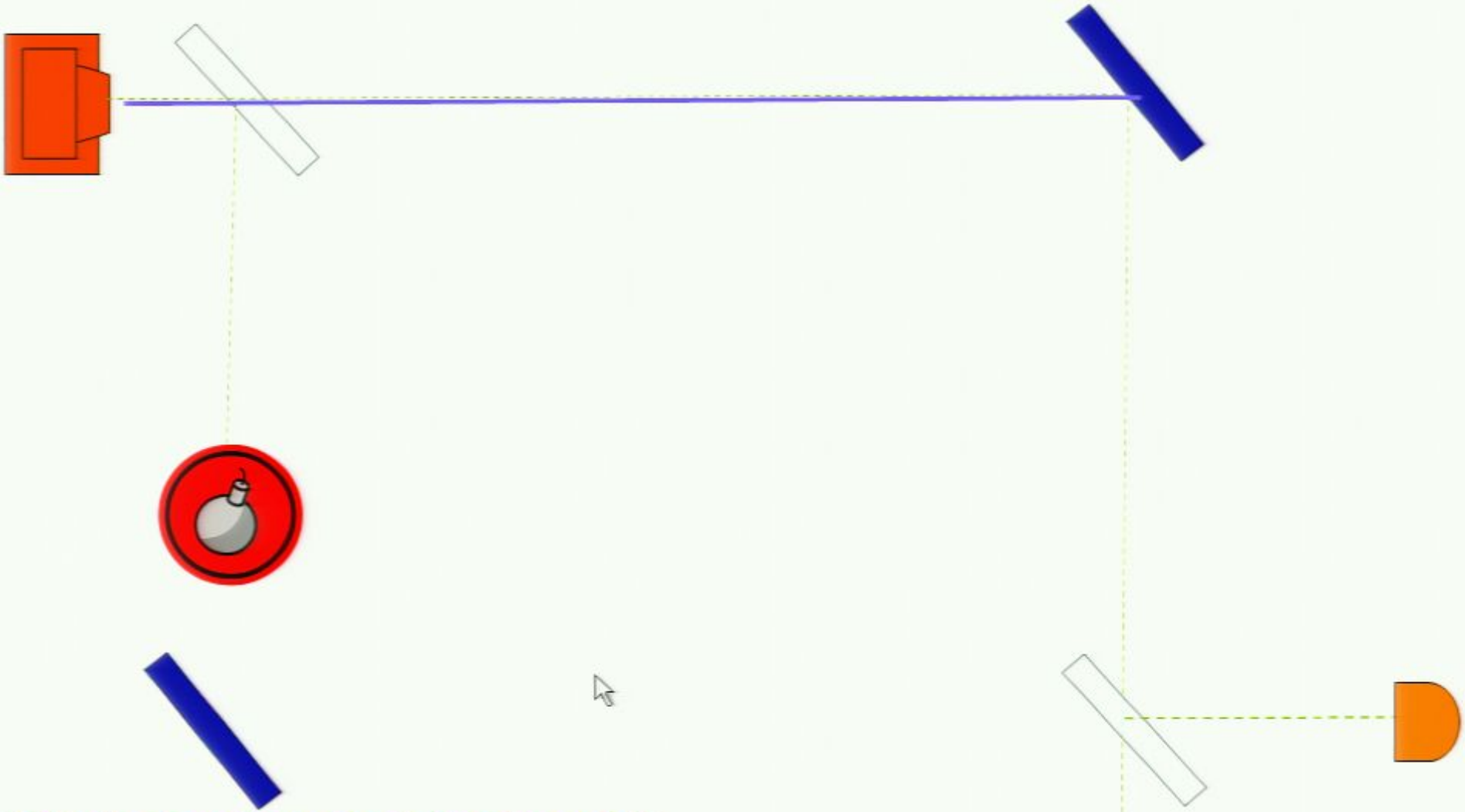

Did photon touched the bomb?

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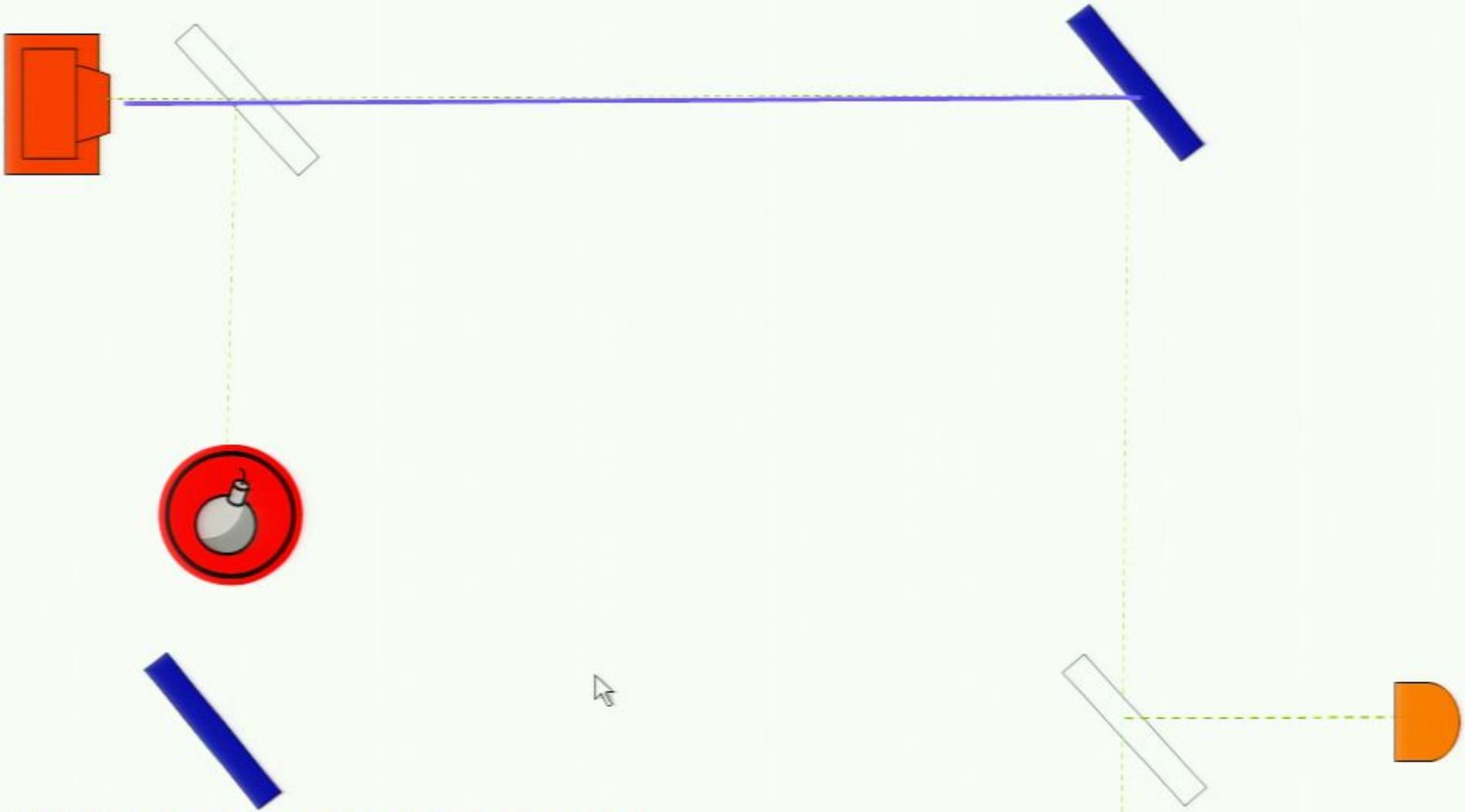

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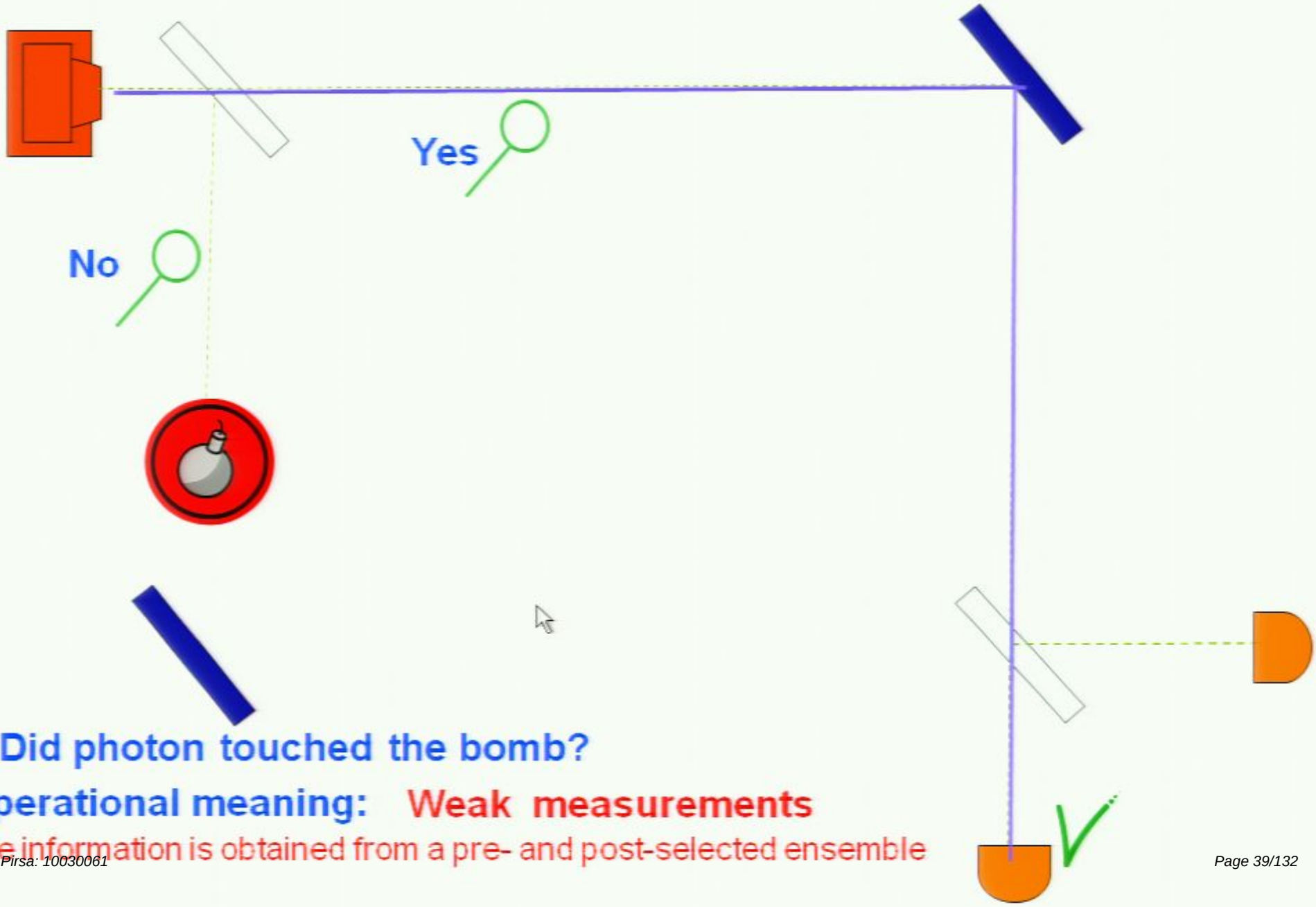

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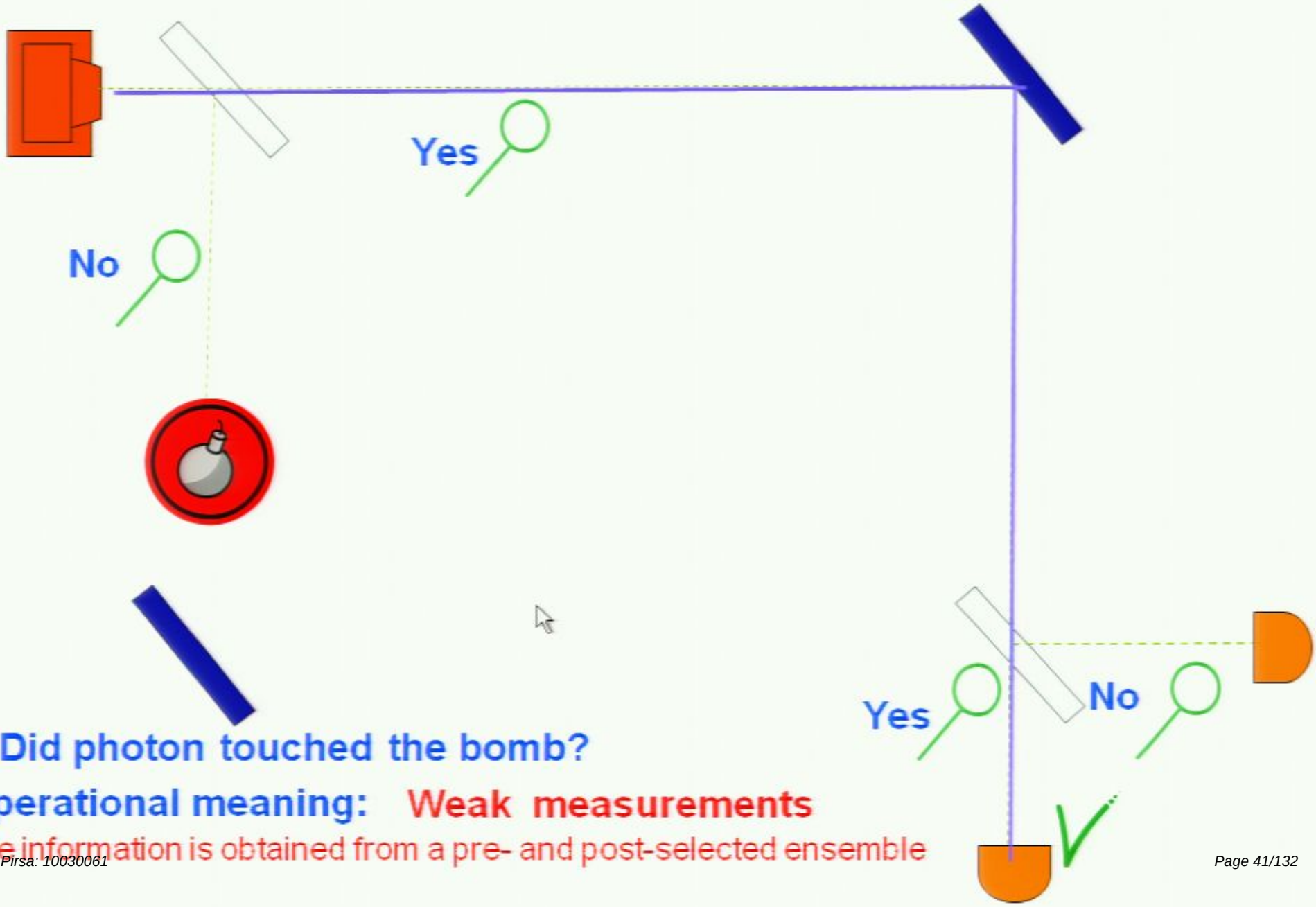

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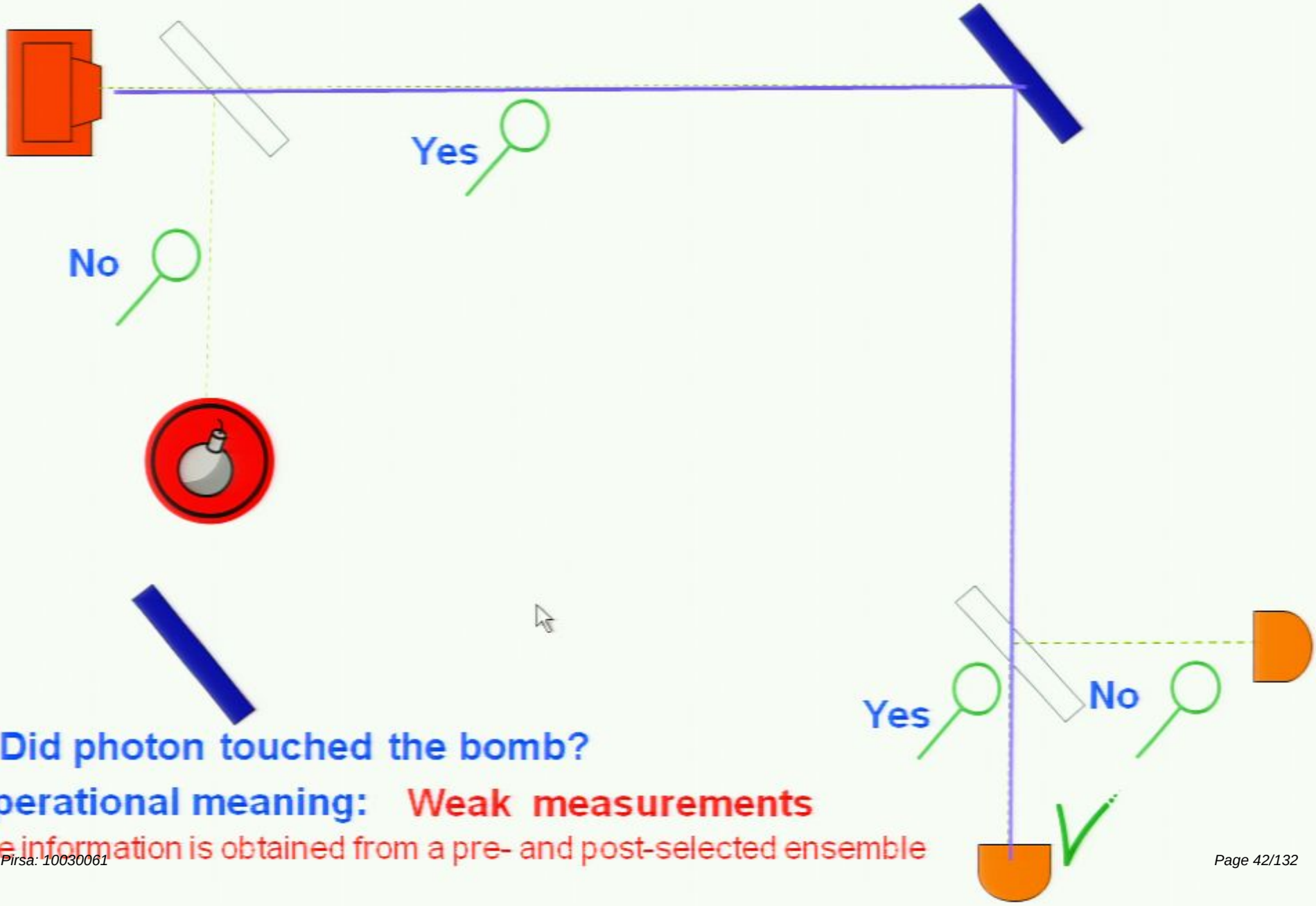

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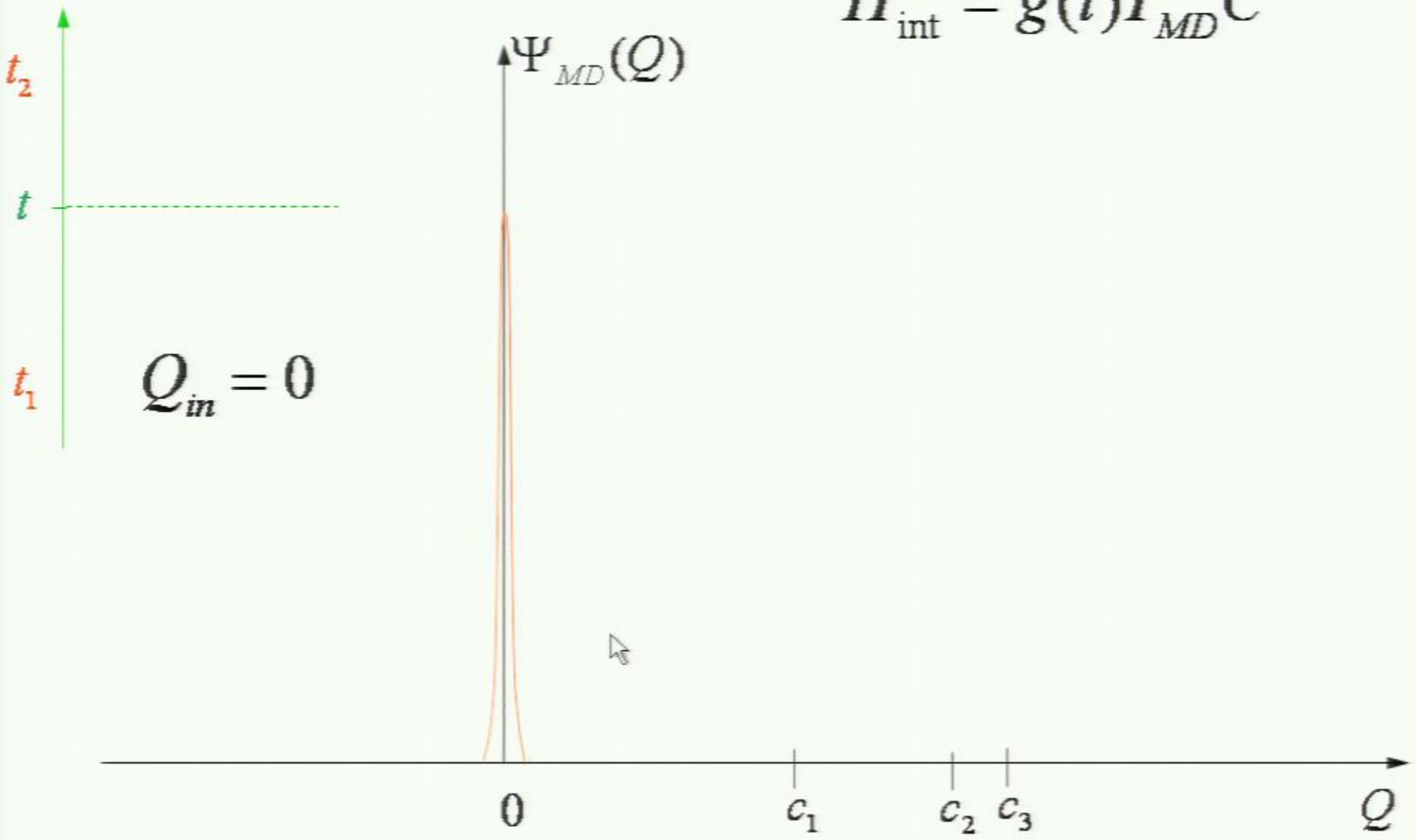
Weak Measurements

Quantum measurement of C

$$H_{\text{int}} = g(t)P_{MD}C$$



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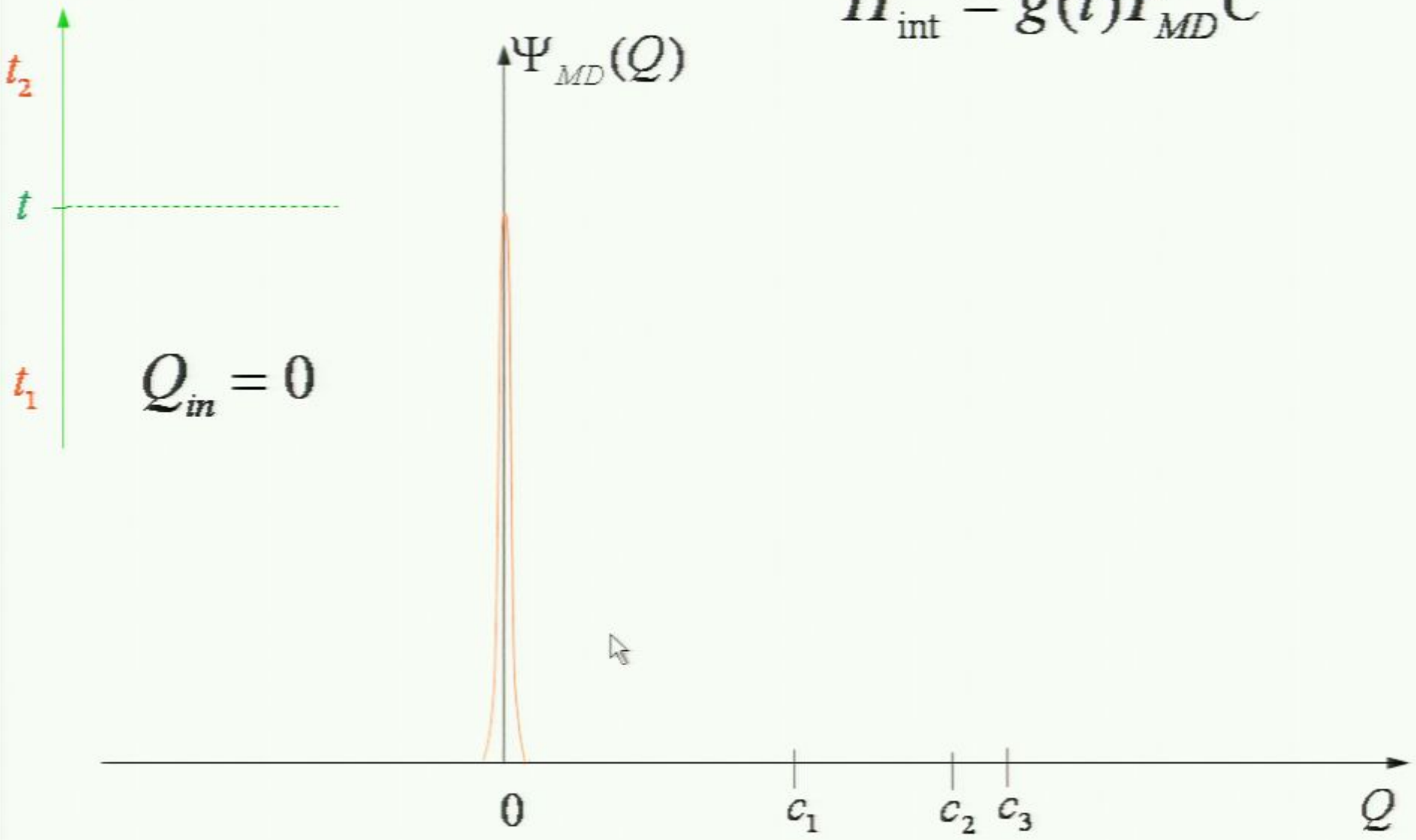

Weak quantum measurement of C

$$H_{\text{int}} = g(t) P_{MD} C$$

$$\langle P_{MD} \rangle = 0, \quad \Delta P_{MD} \text{ small}$$

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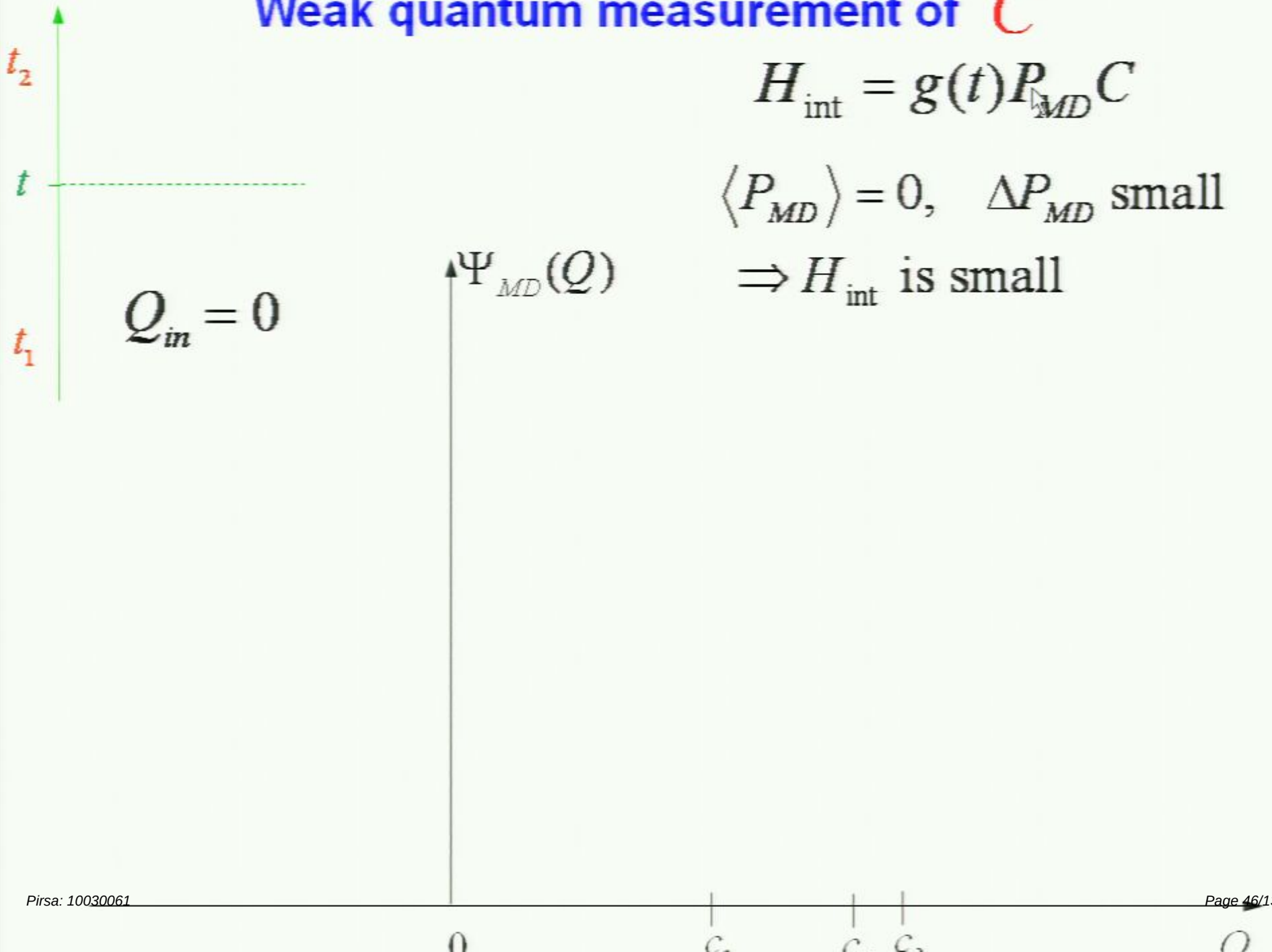

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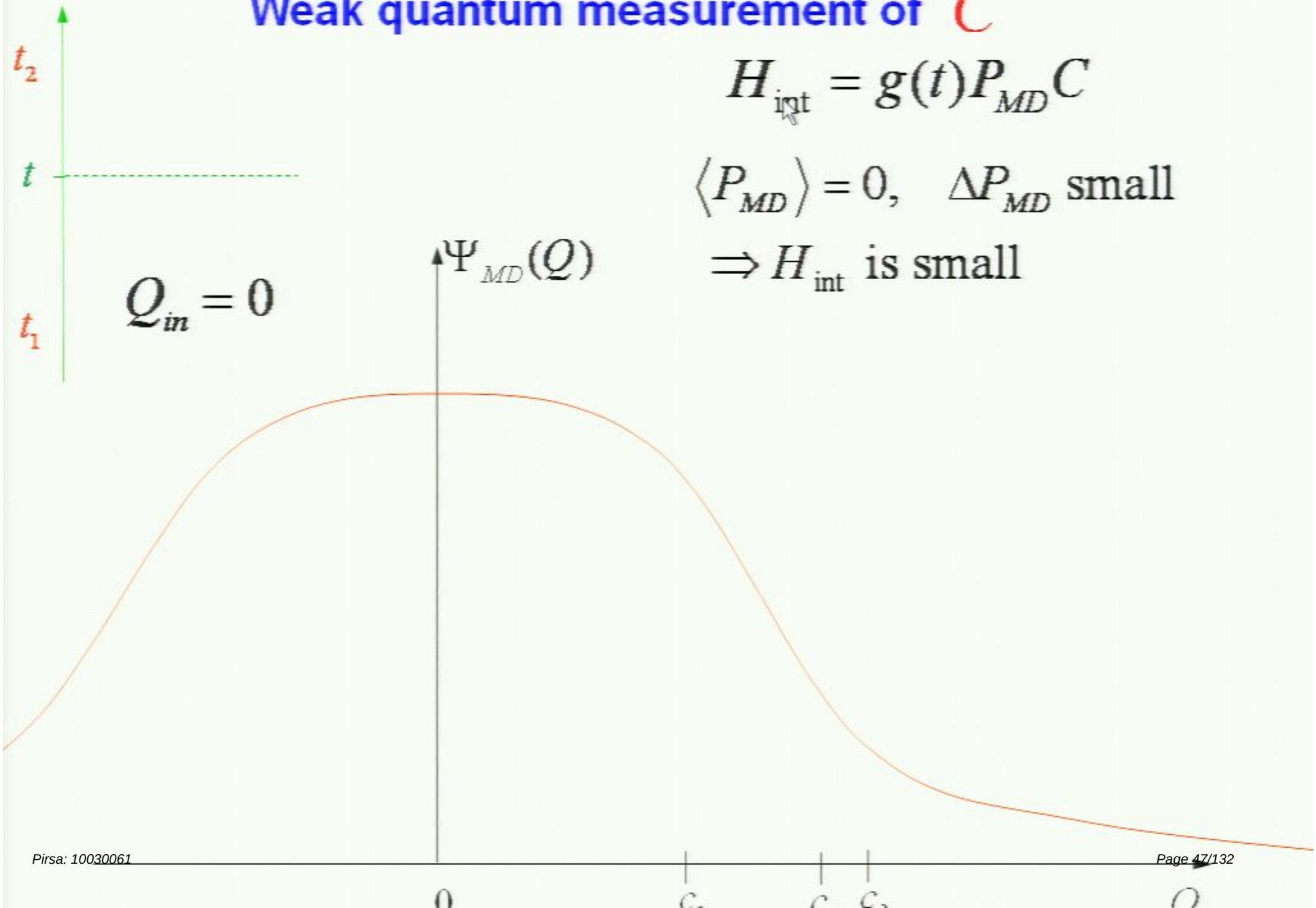

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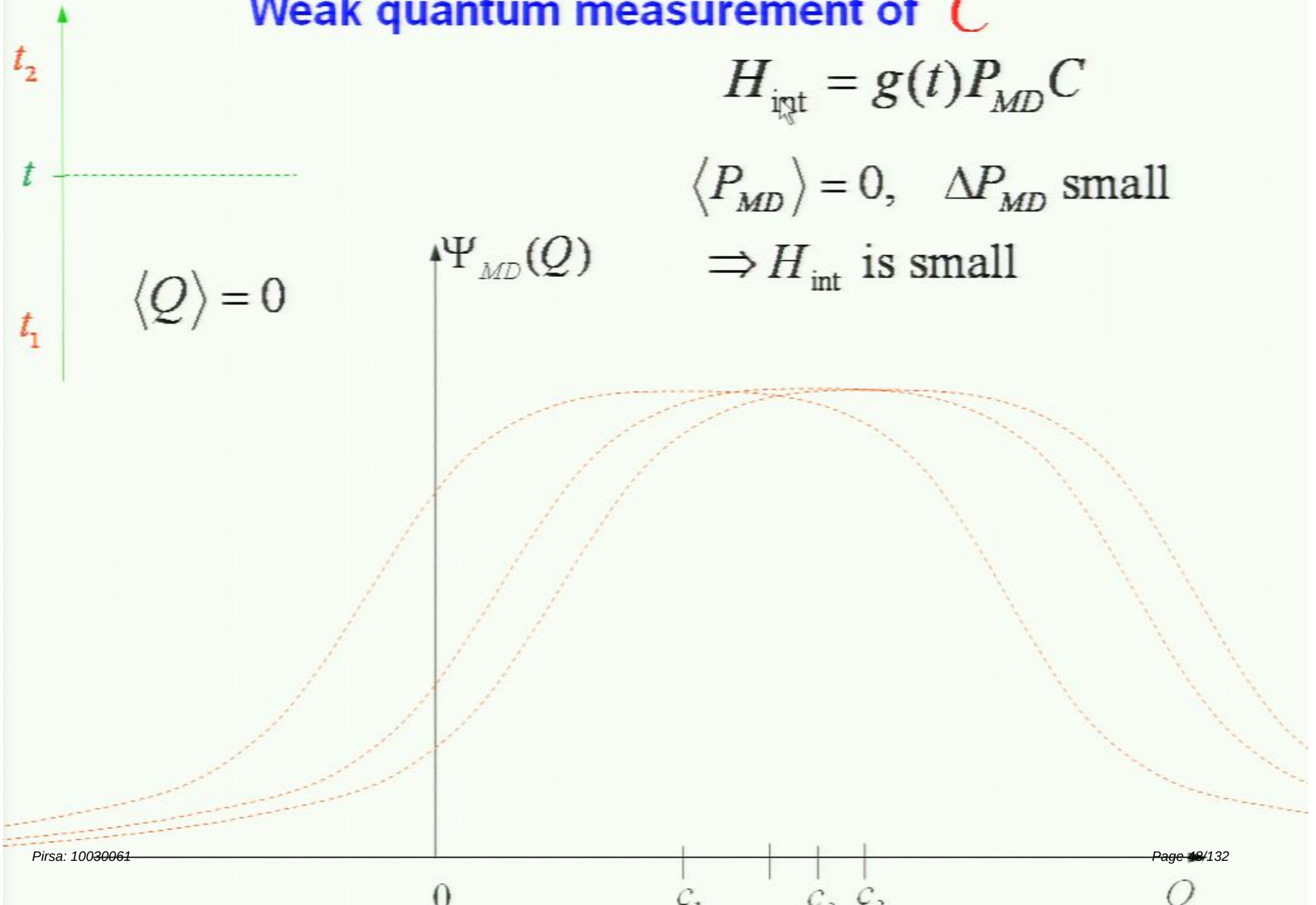

Weak quantum measurement of C

t_2

$\langle Q_{fin} \rangle = \langle C \rangle$

t

$\langle Q \rangle = 0$

t_1

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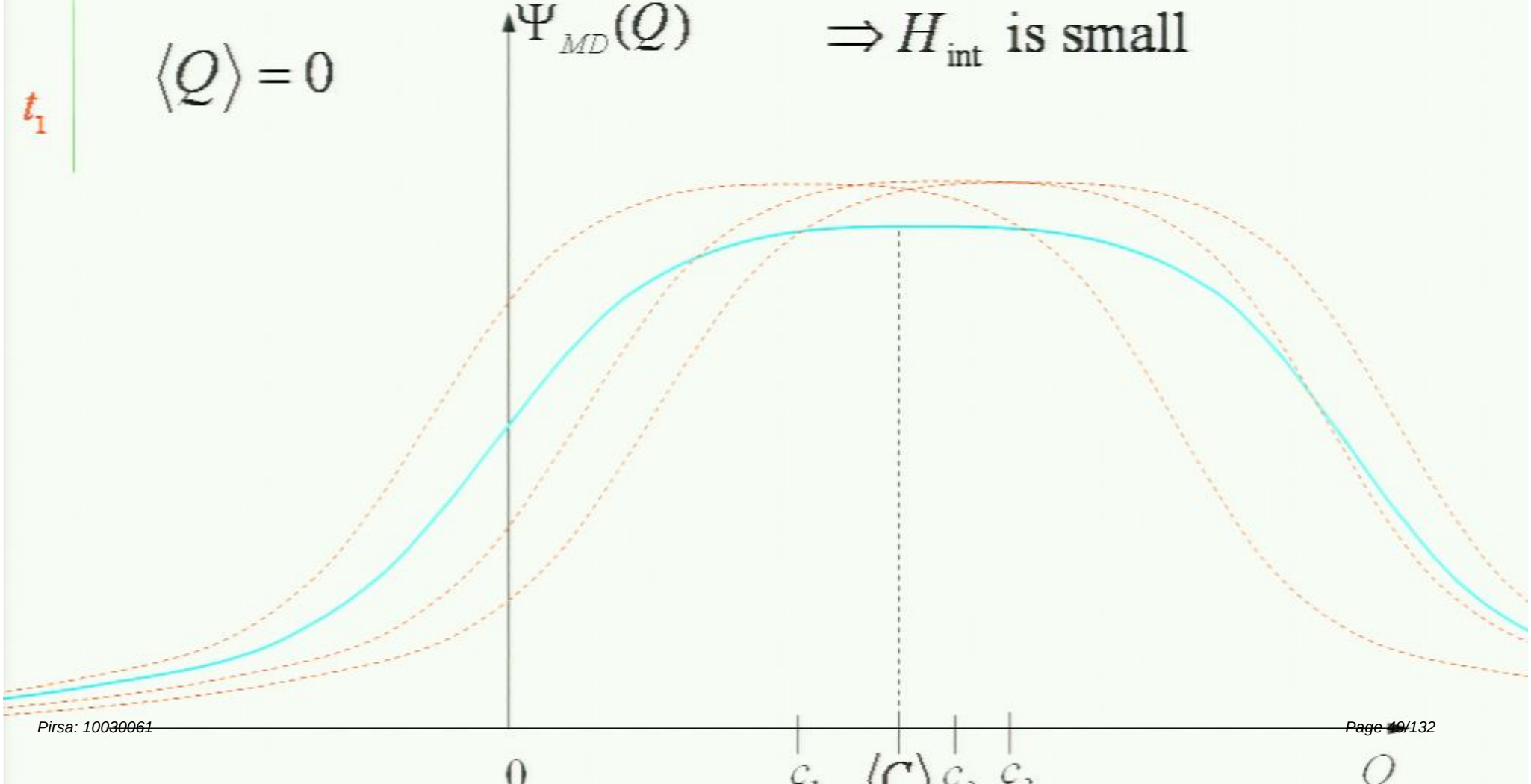

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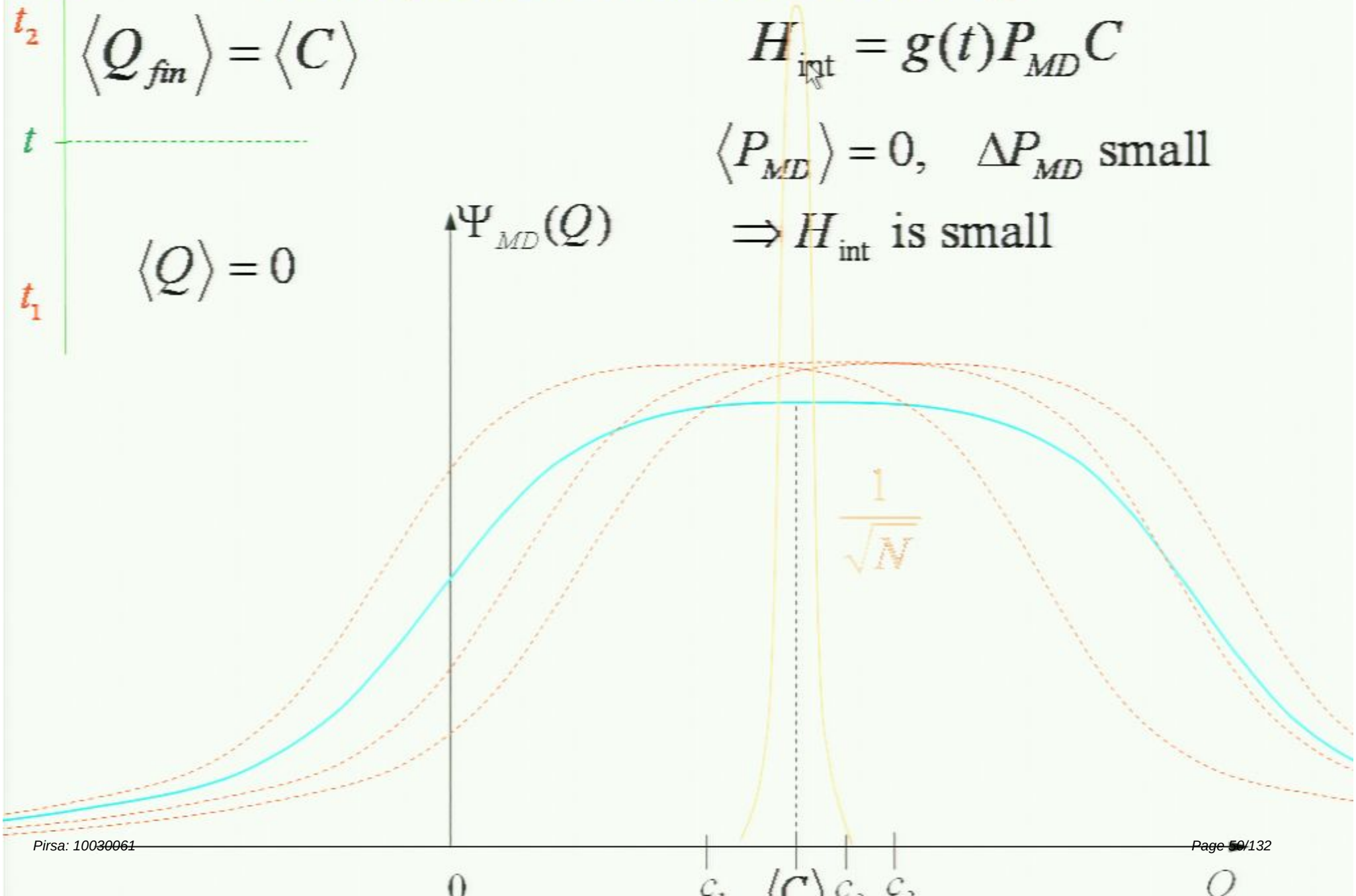
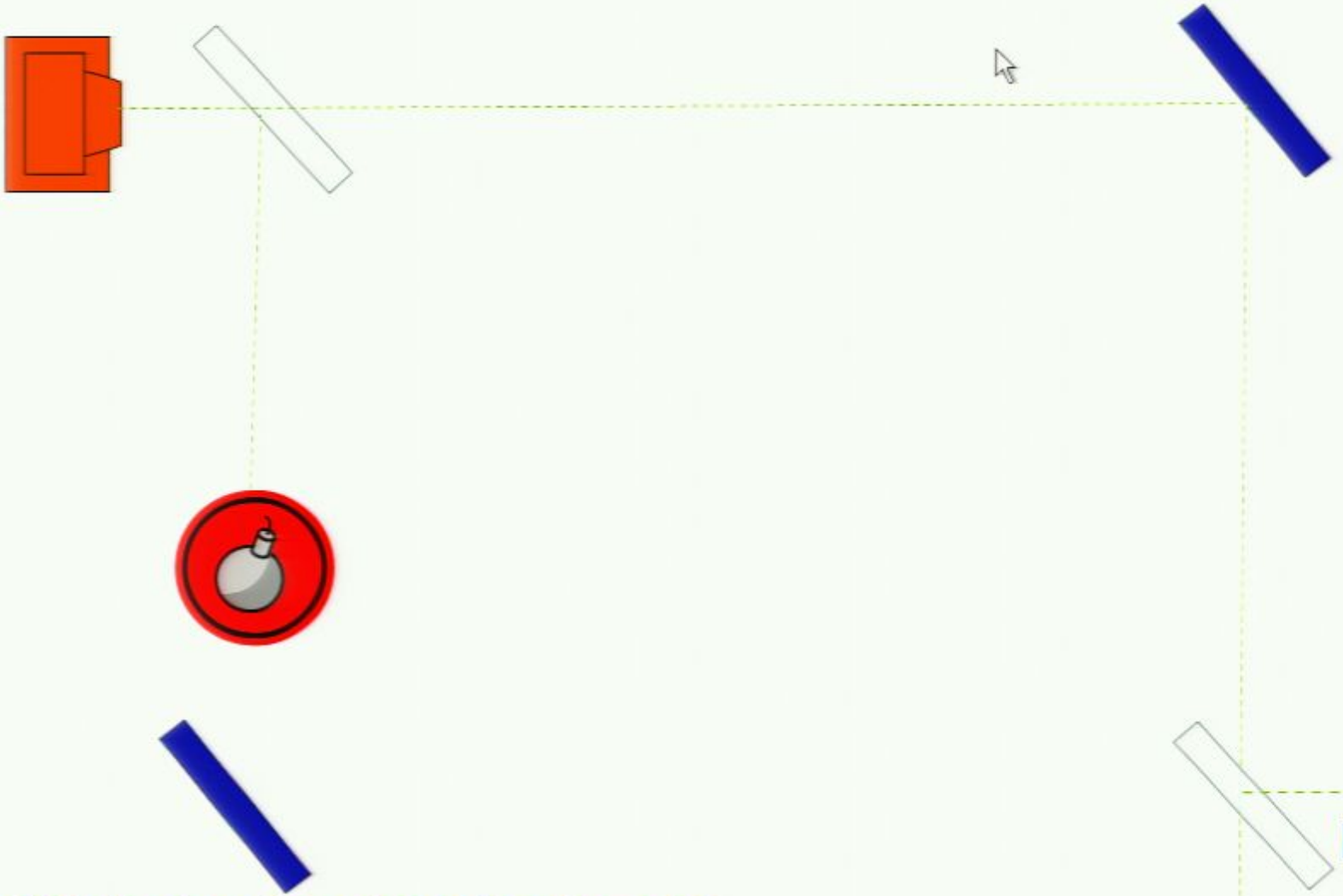


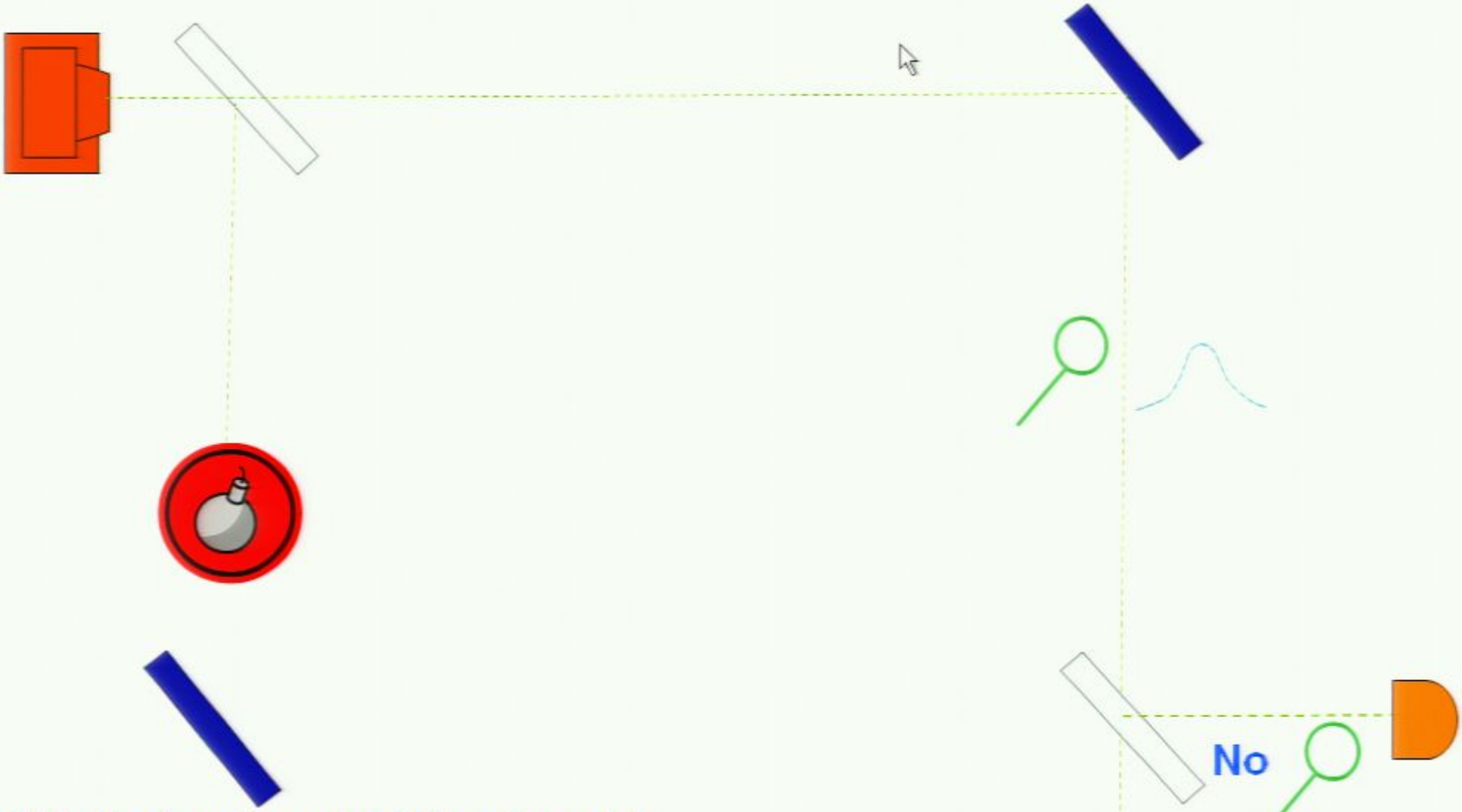
Interaction-free measurement



Did photon touched the bomb?

Operational meaning: Strong measurements

Interaction-free measurement



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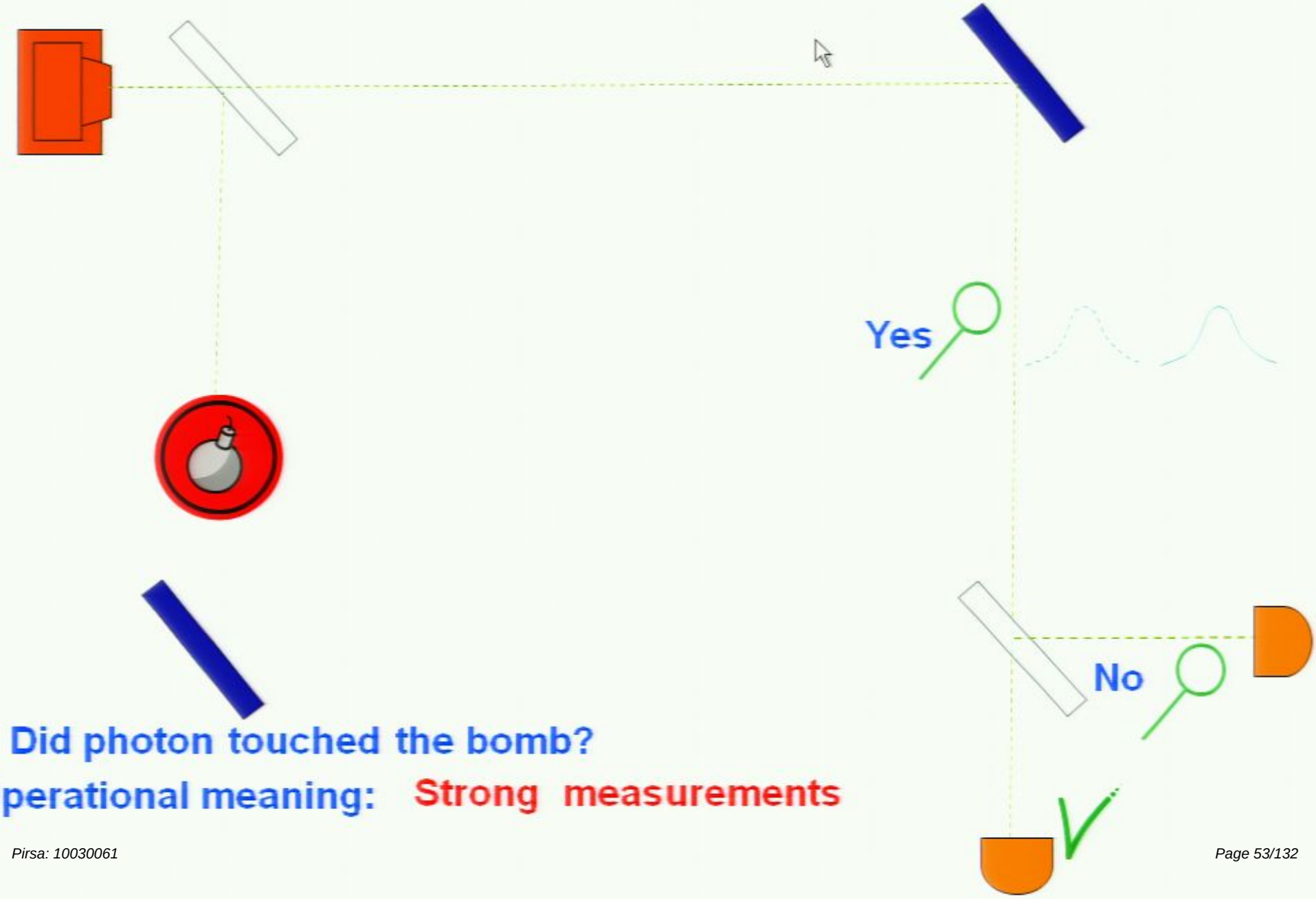

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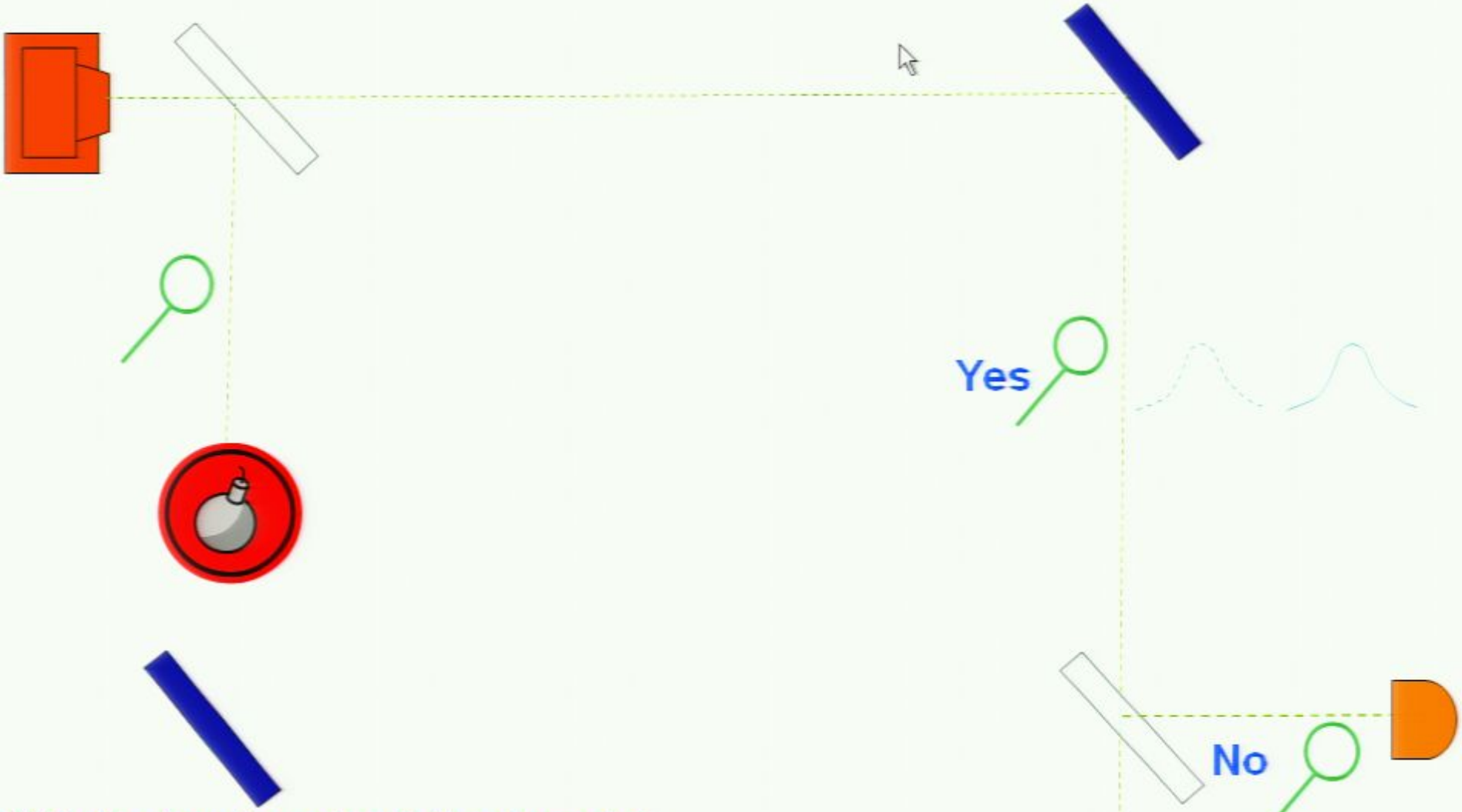

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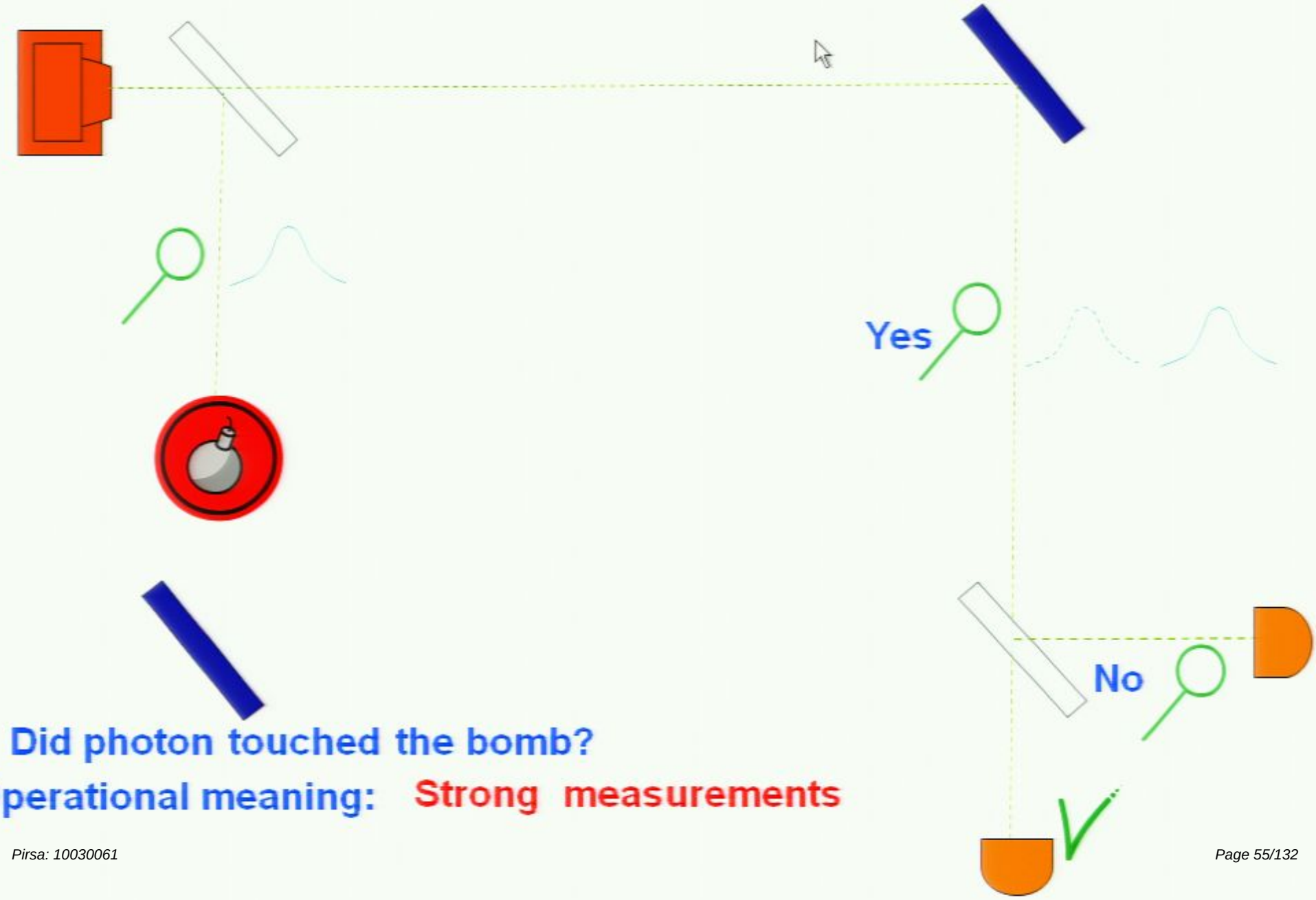

Did photon touched the bomb?

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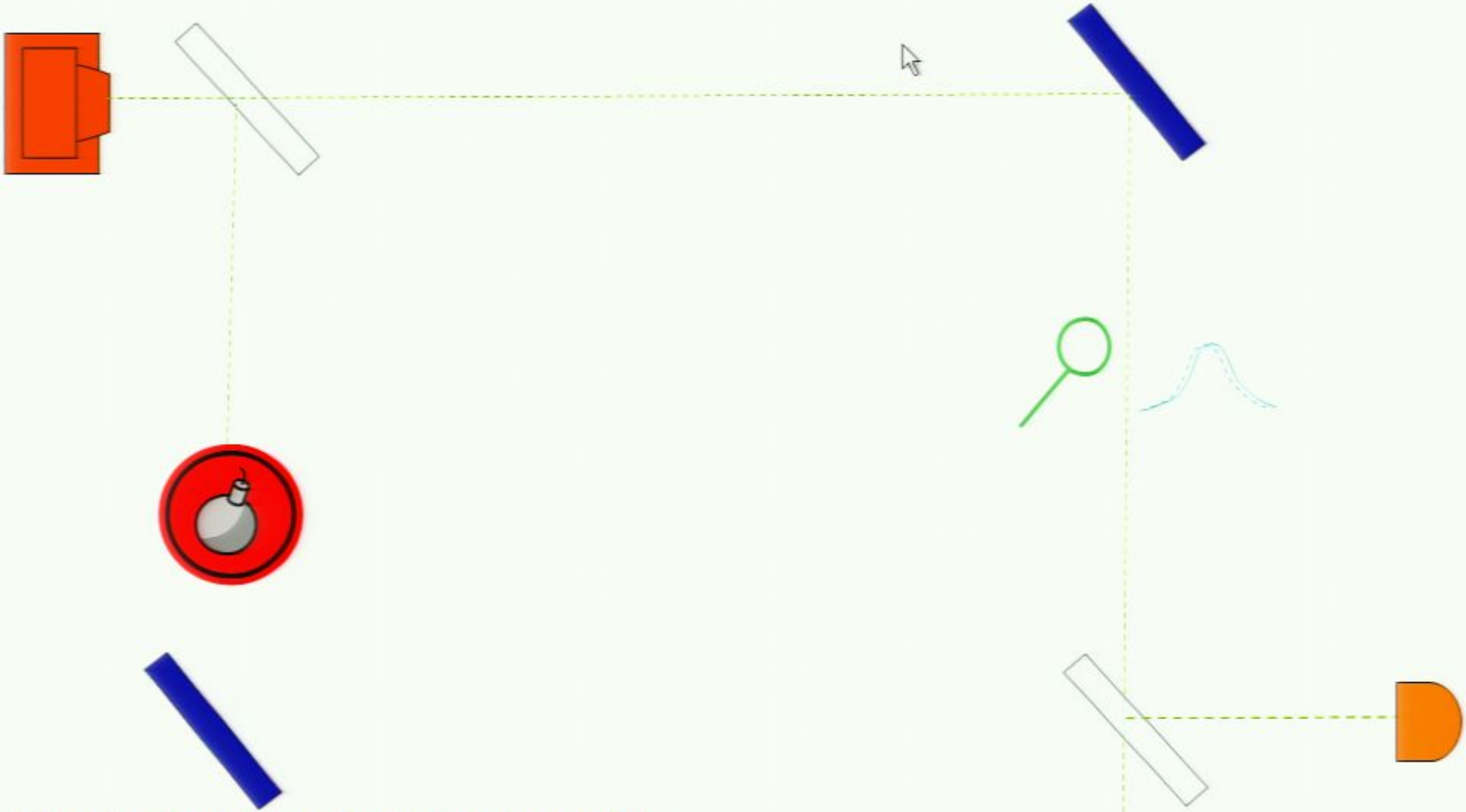

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The information is obtained from a pre- and post-selected ensemble

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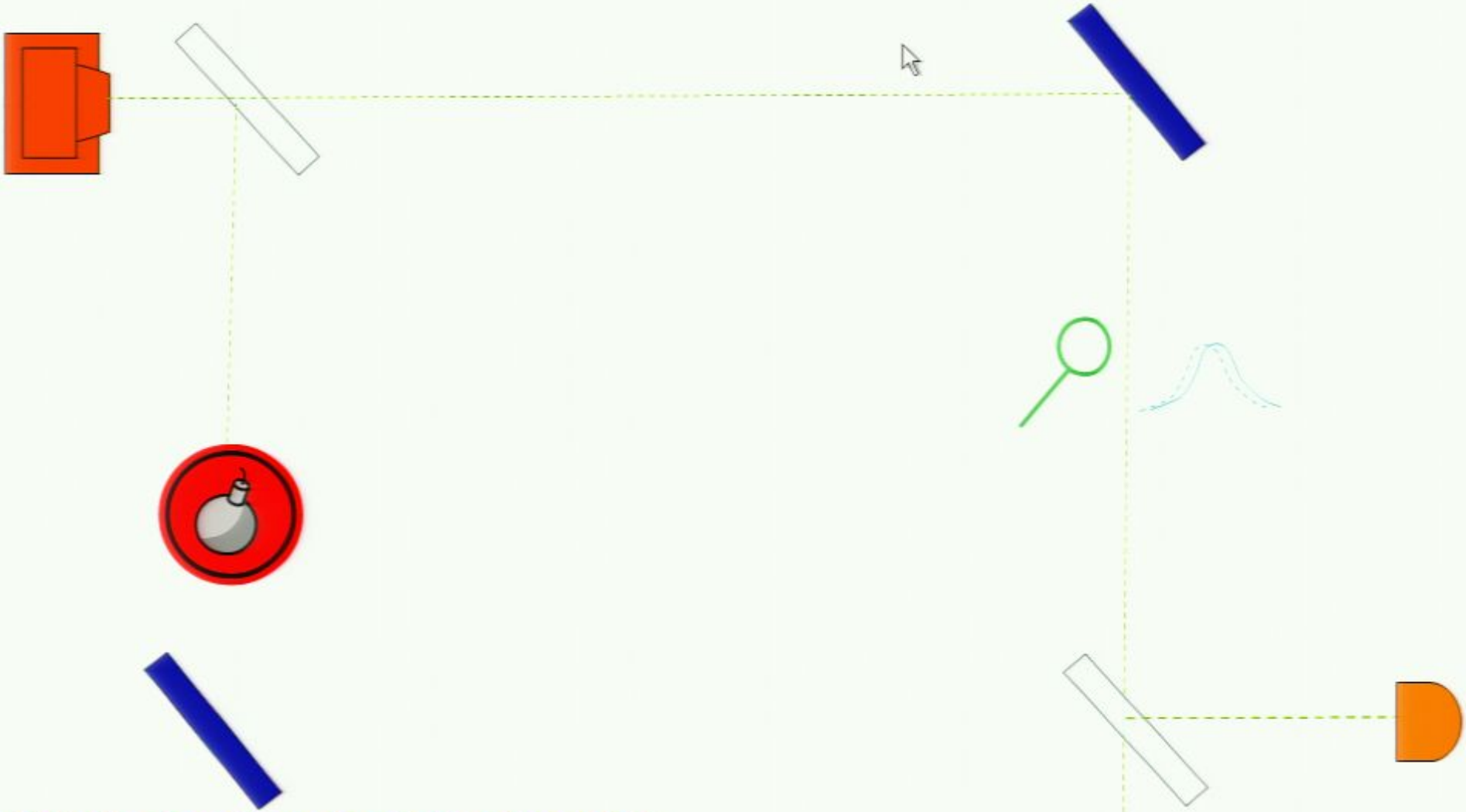

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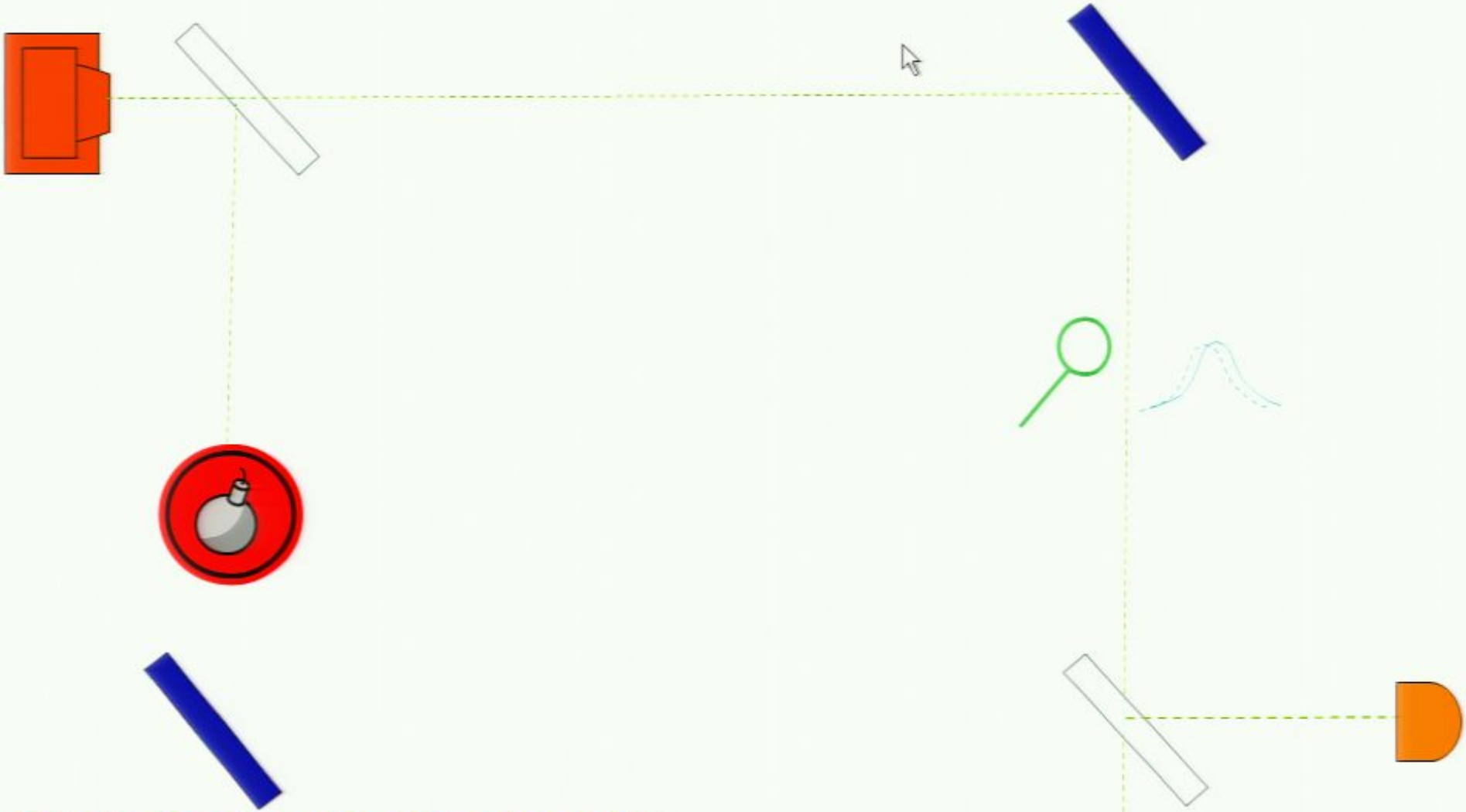

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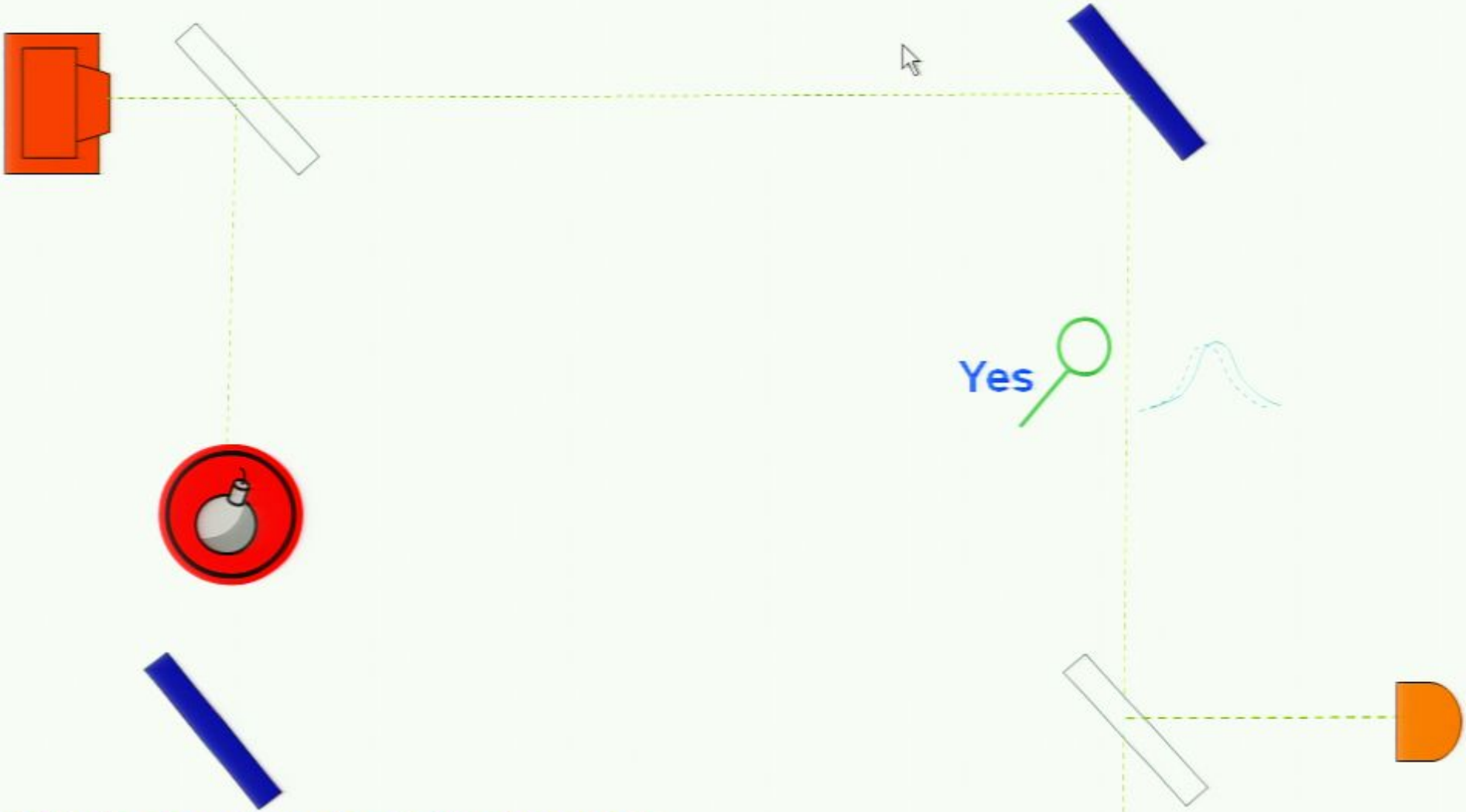

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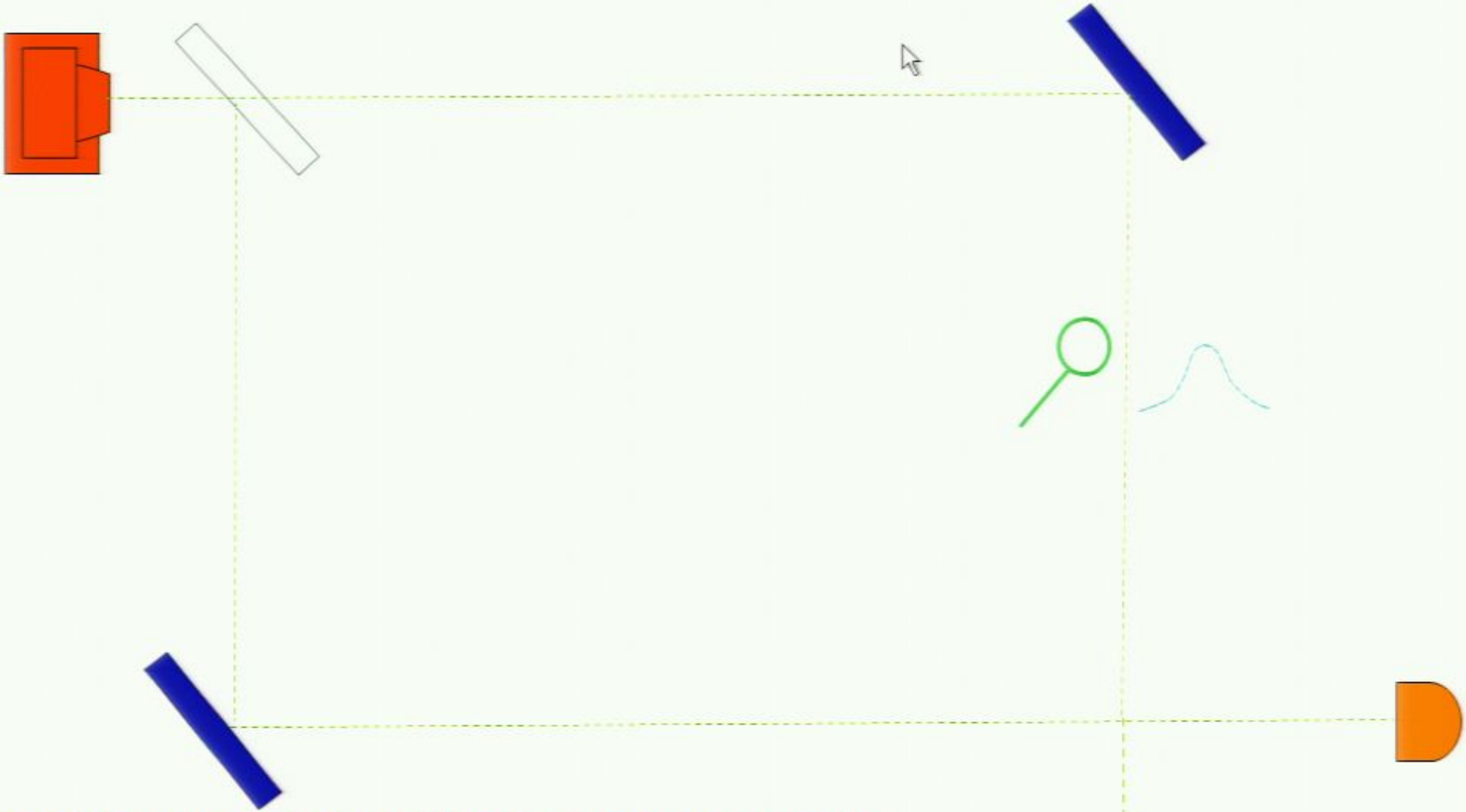
Wheeler delayed choice experiment



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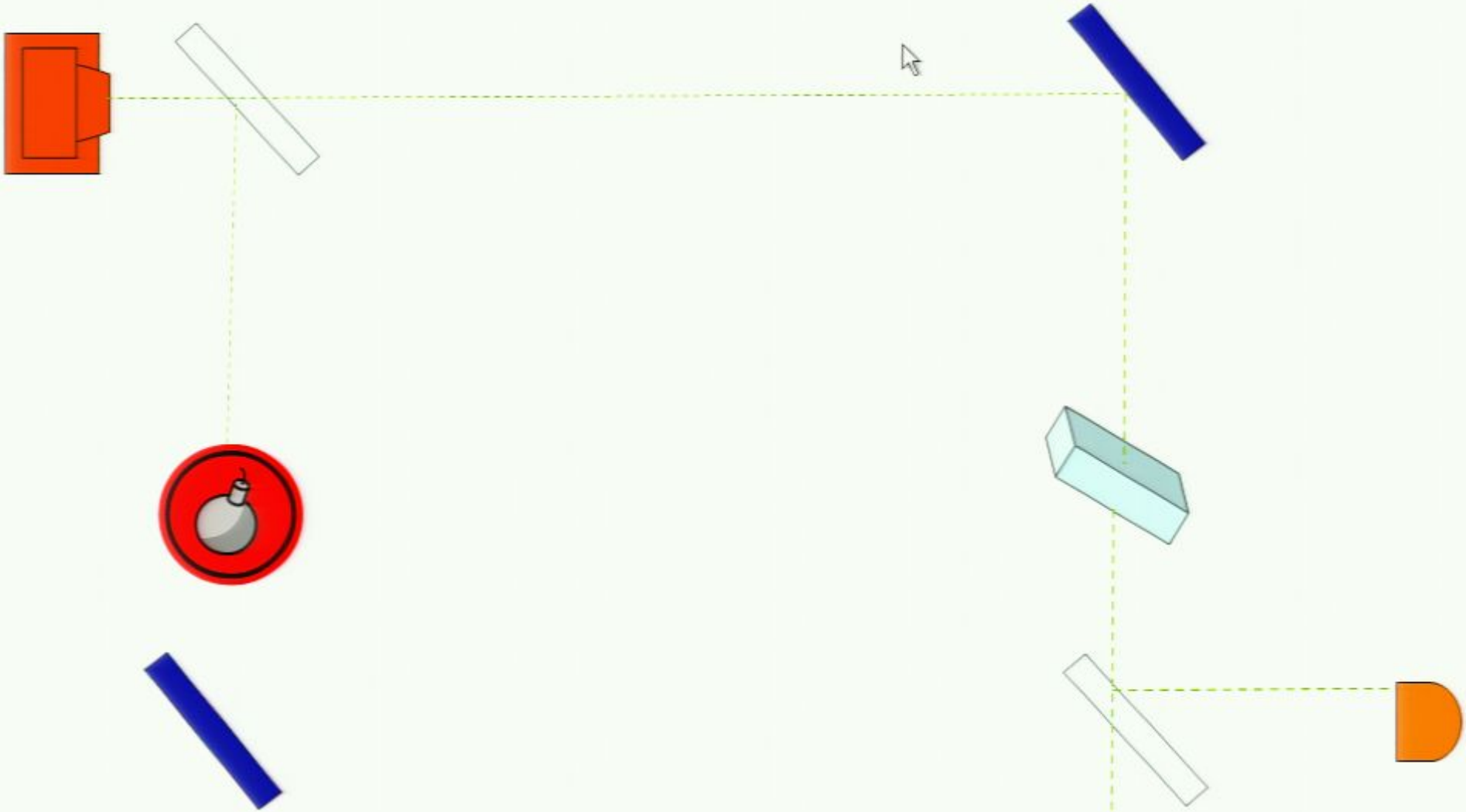

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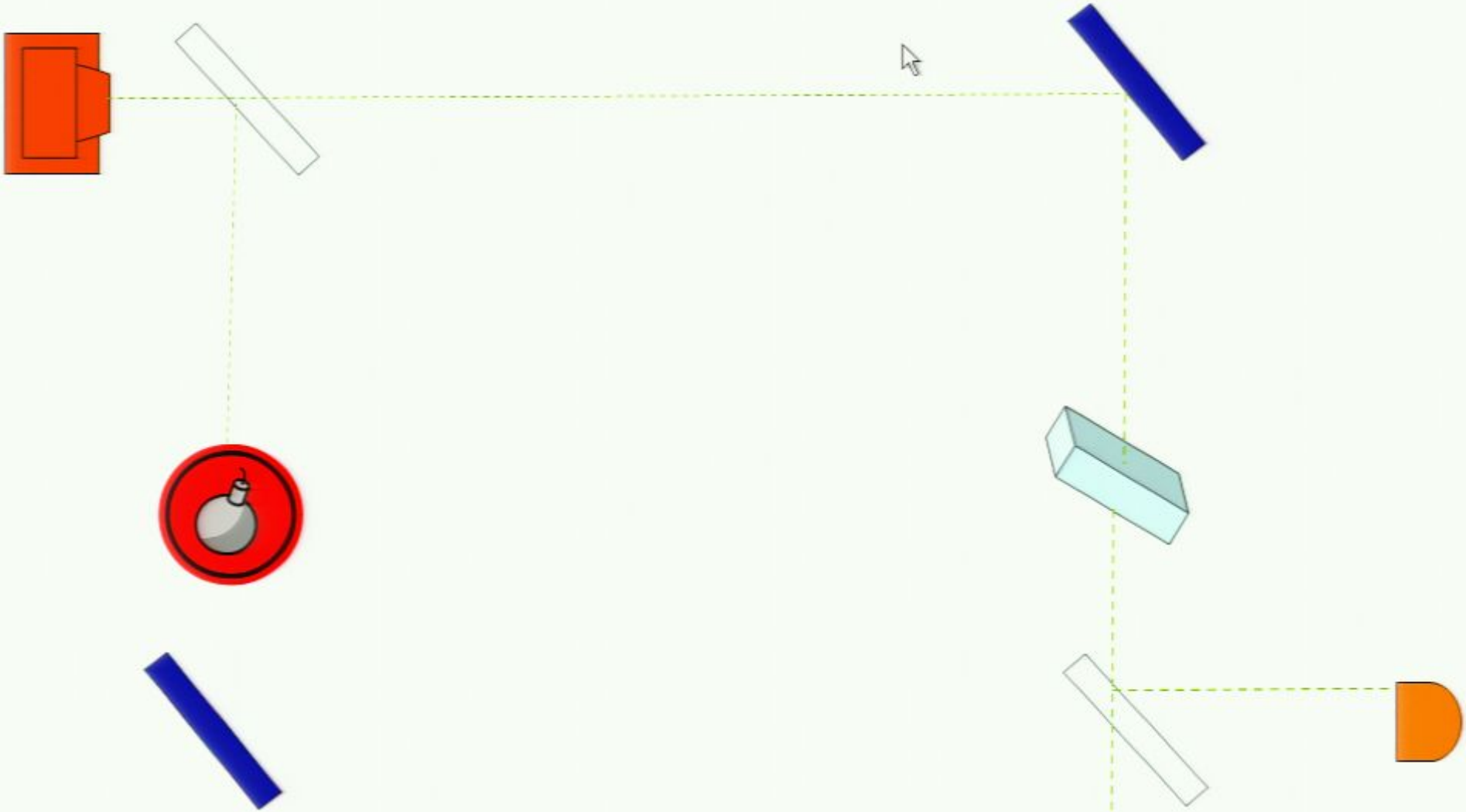
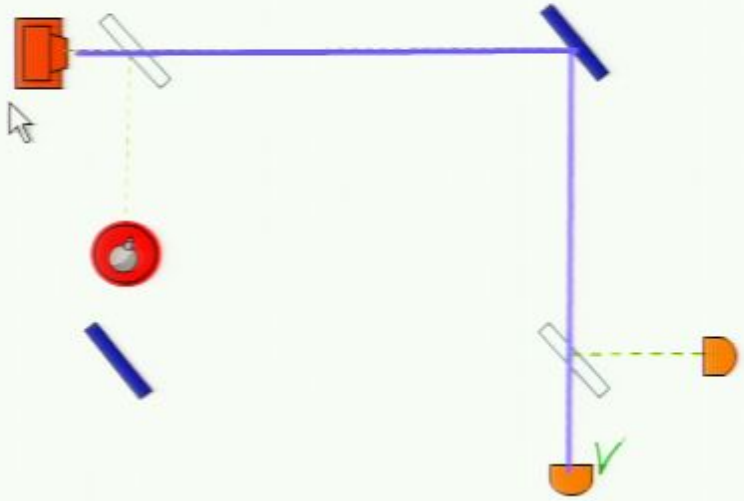


Wheeler's argument:

"The photon took the upper path because it could not come the other way" seems to be sound.



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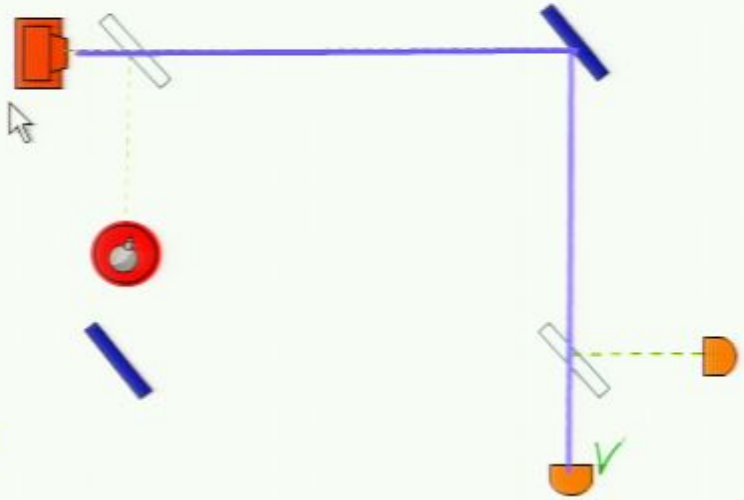

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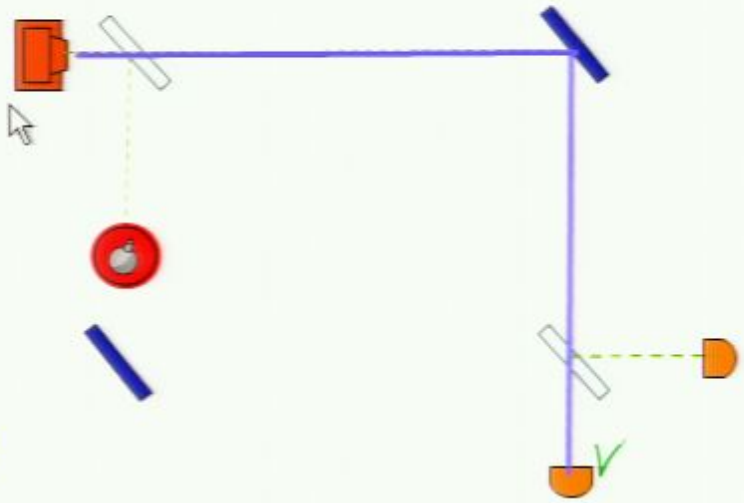

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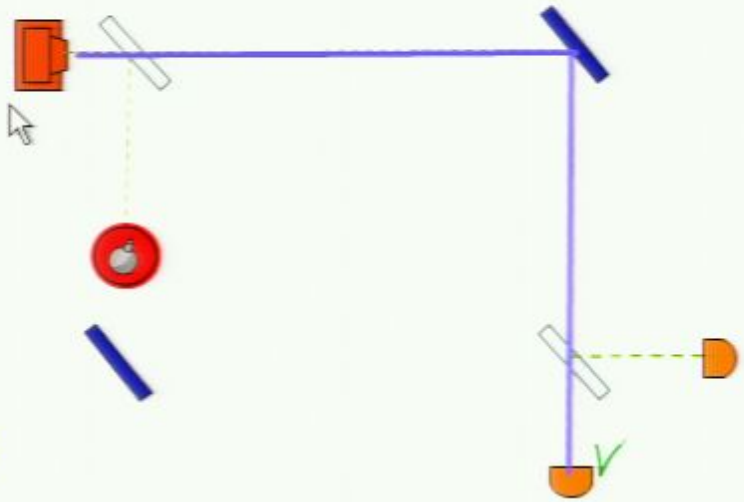

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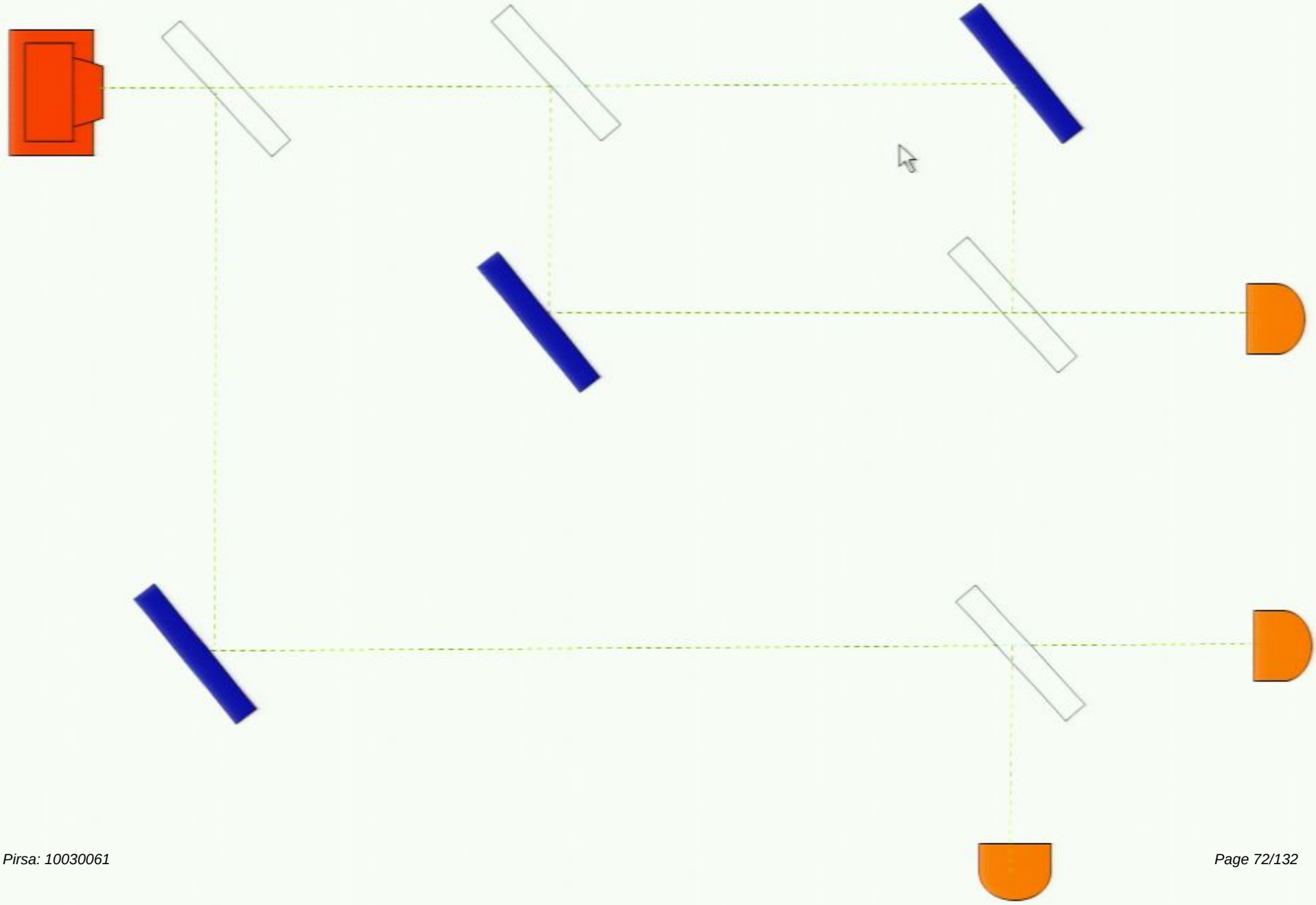
Kwiat's proposal



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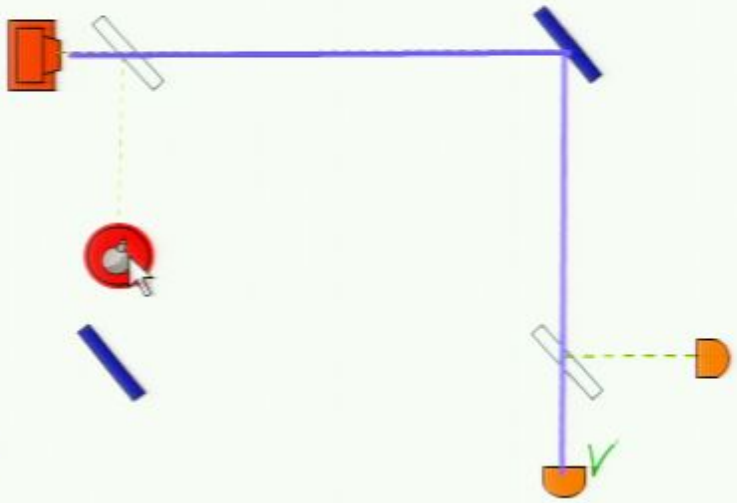

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Hosten,…Kwiat, *Nature* **439**, 949 (2006) **Yes!**

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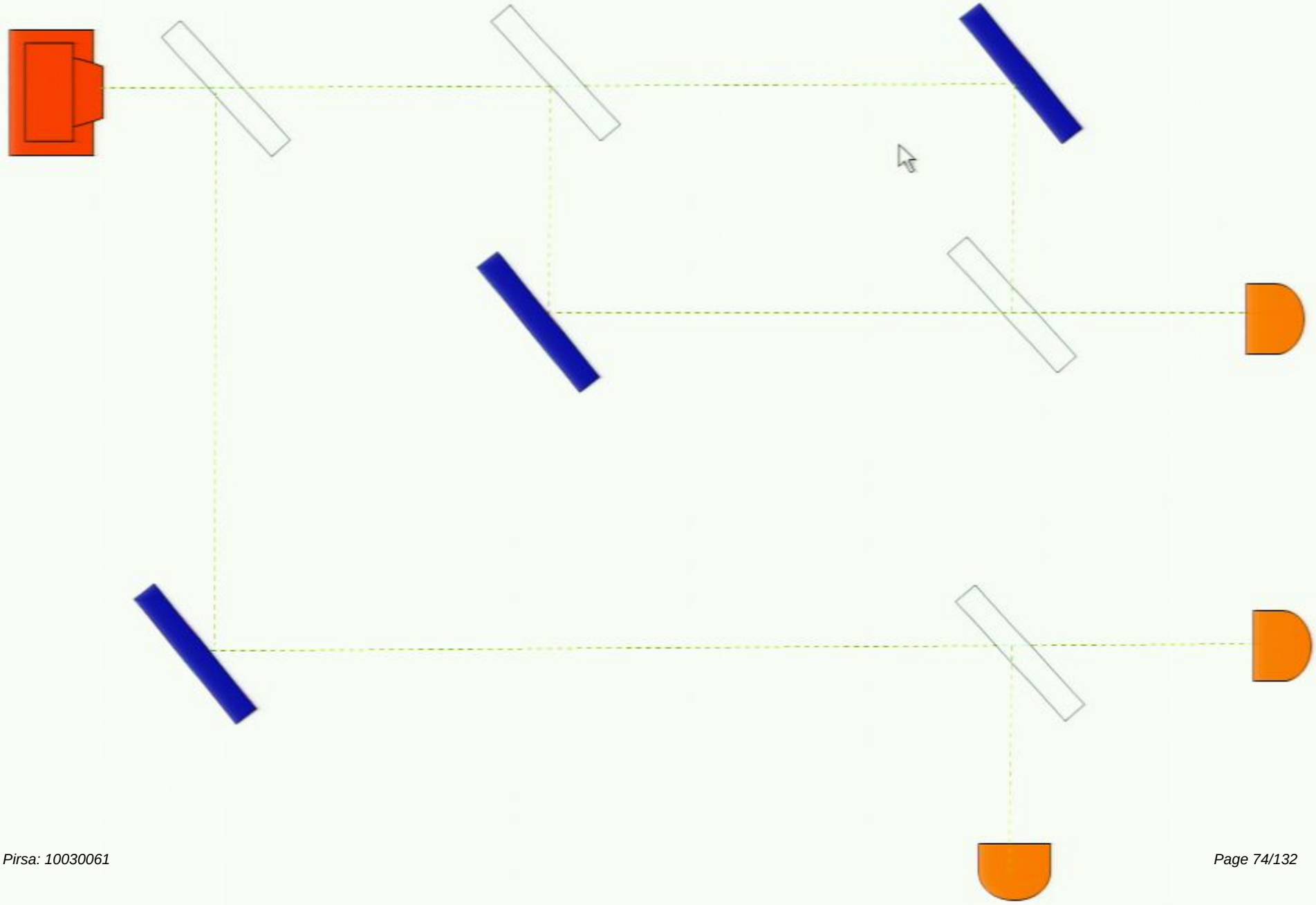

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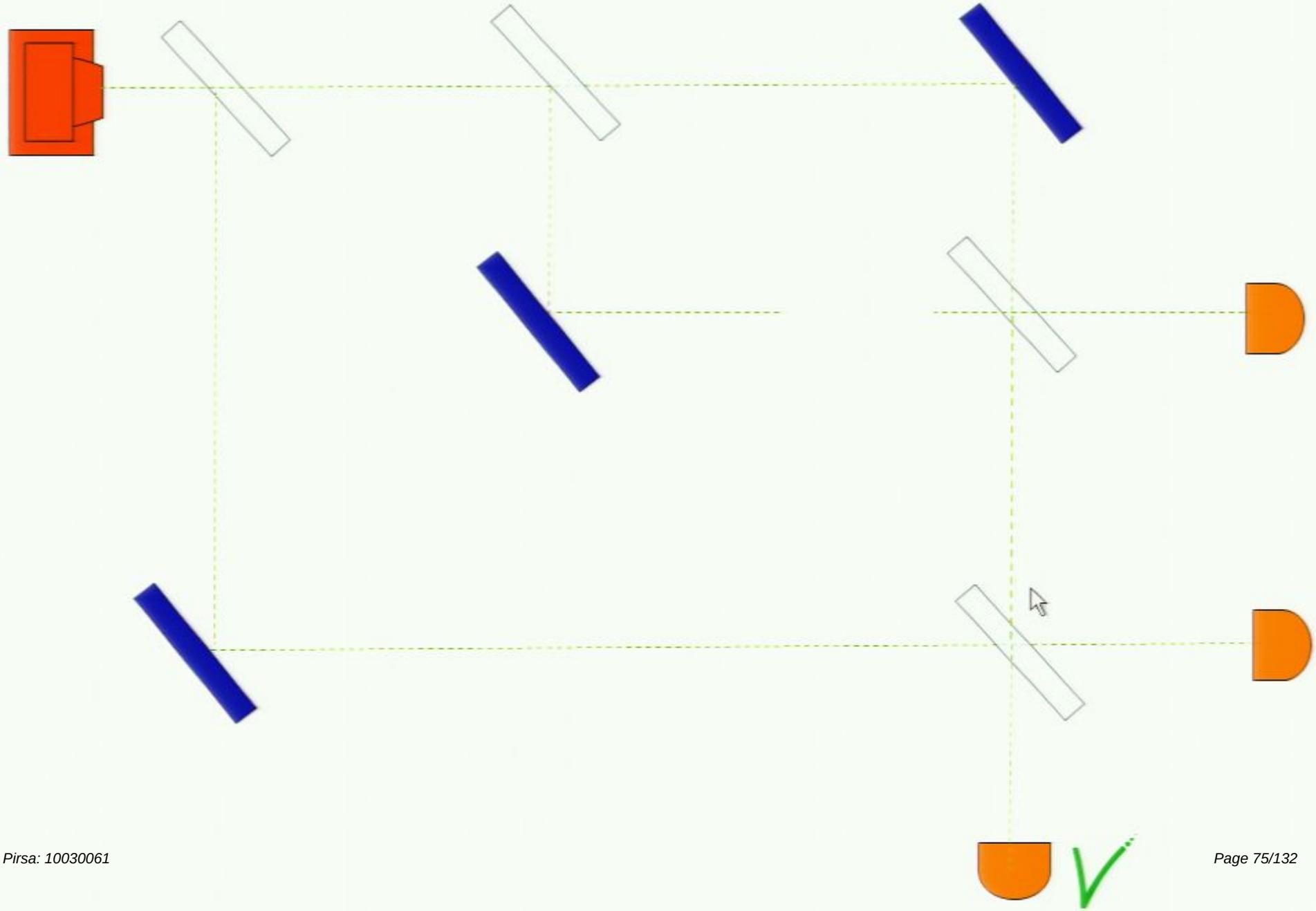

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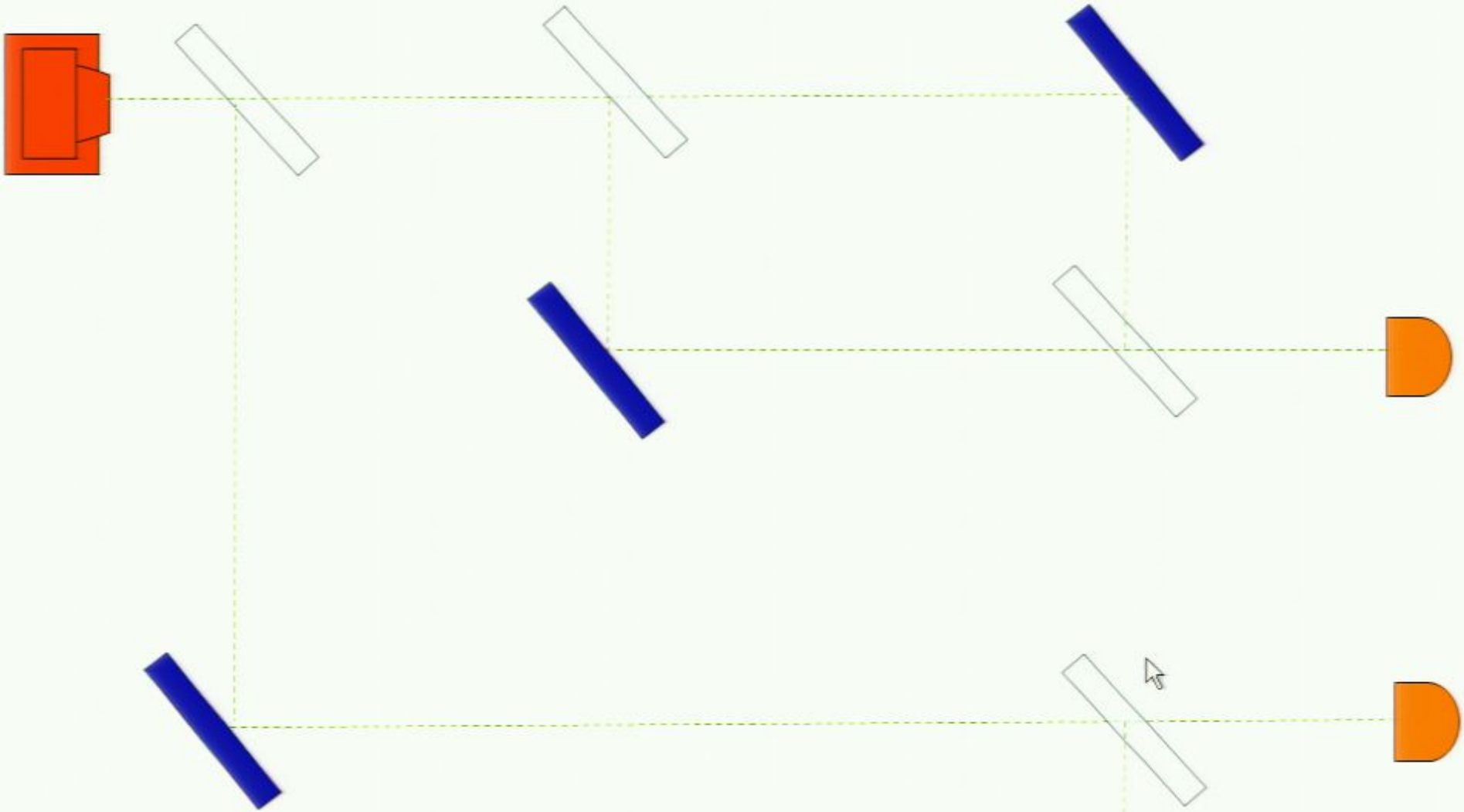

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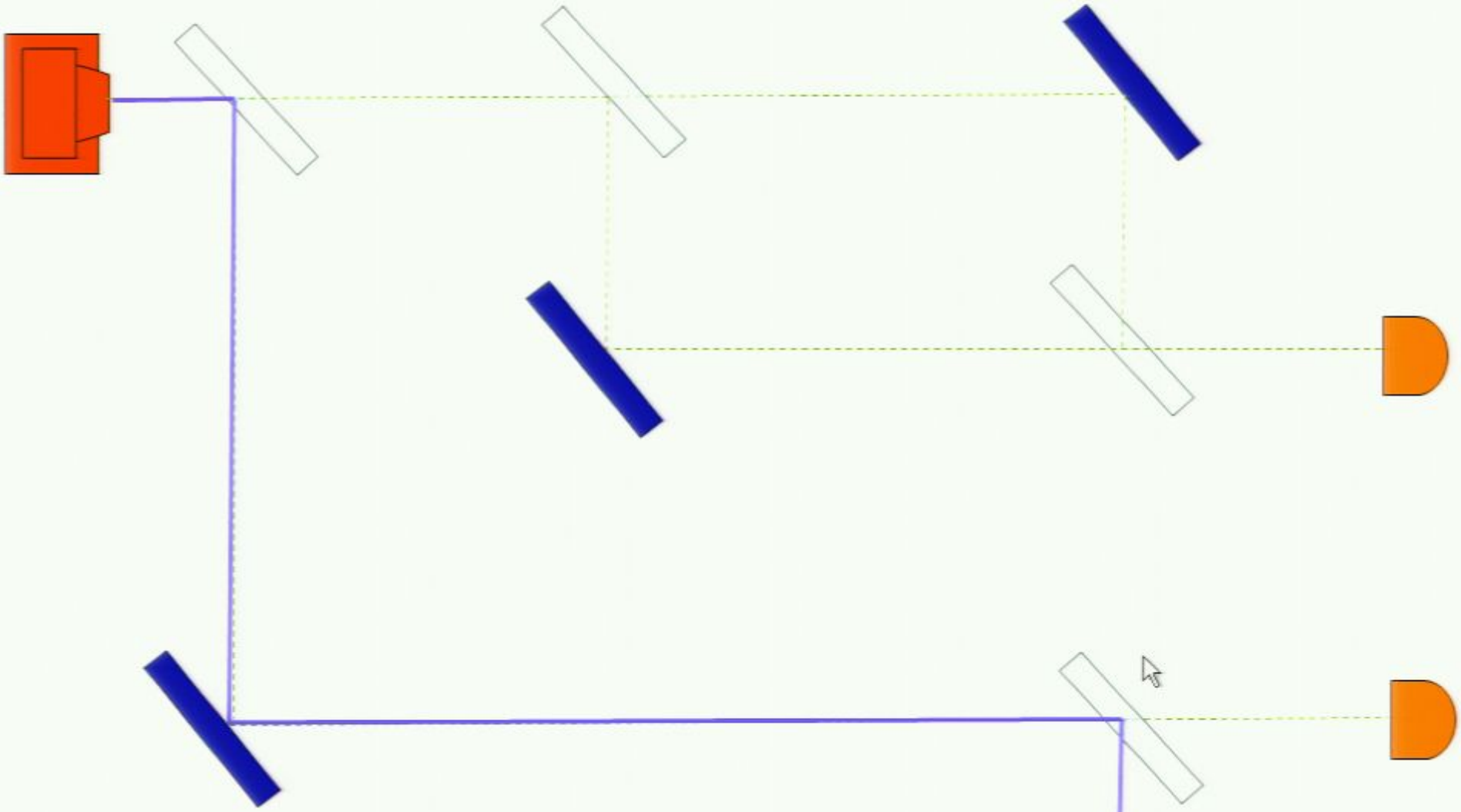

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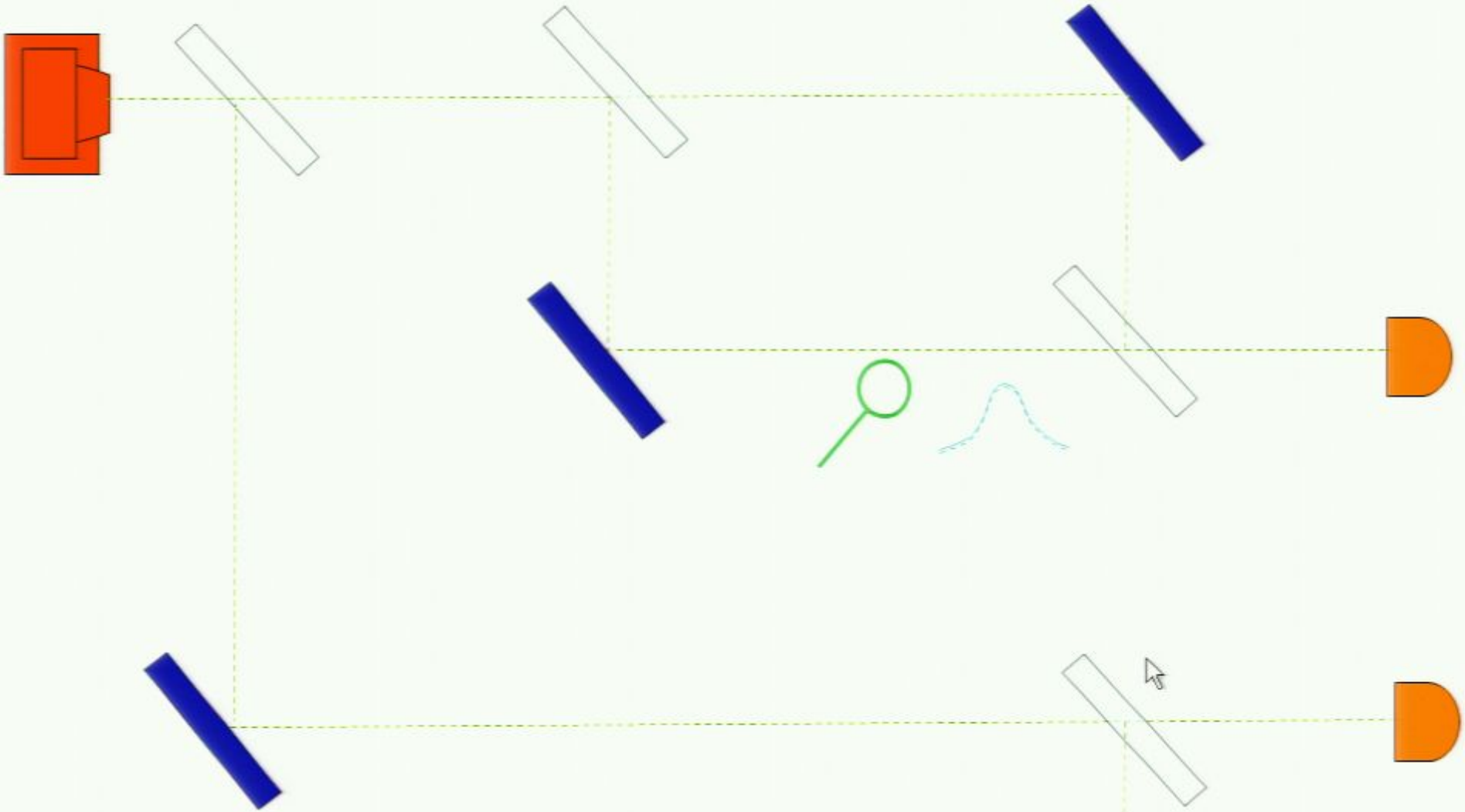

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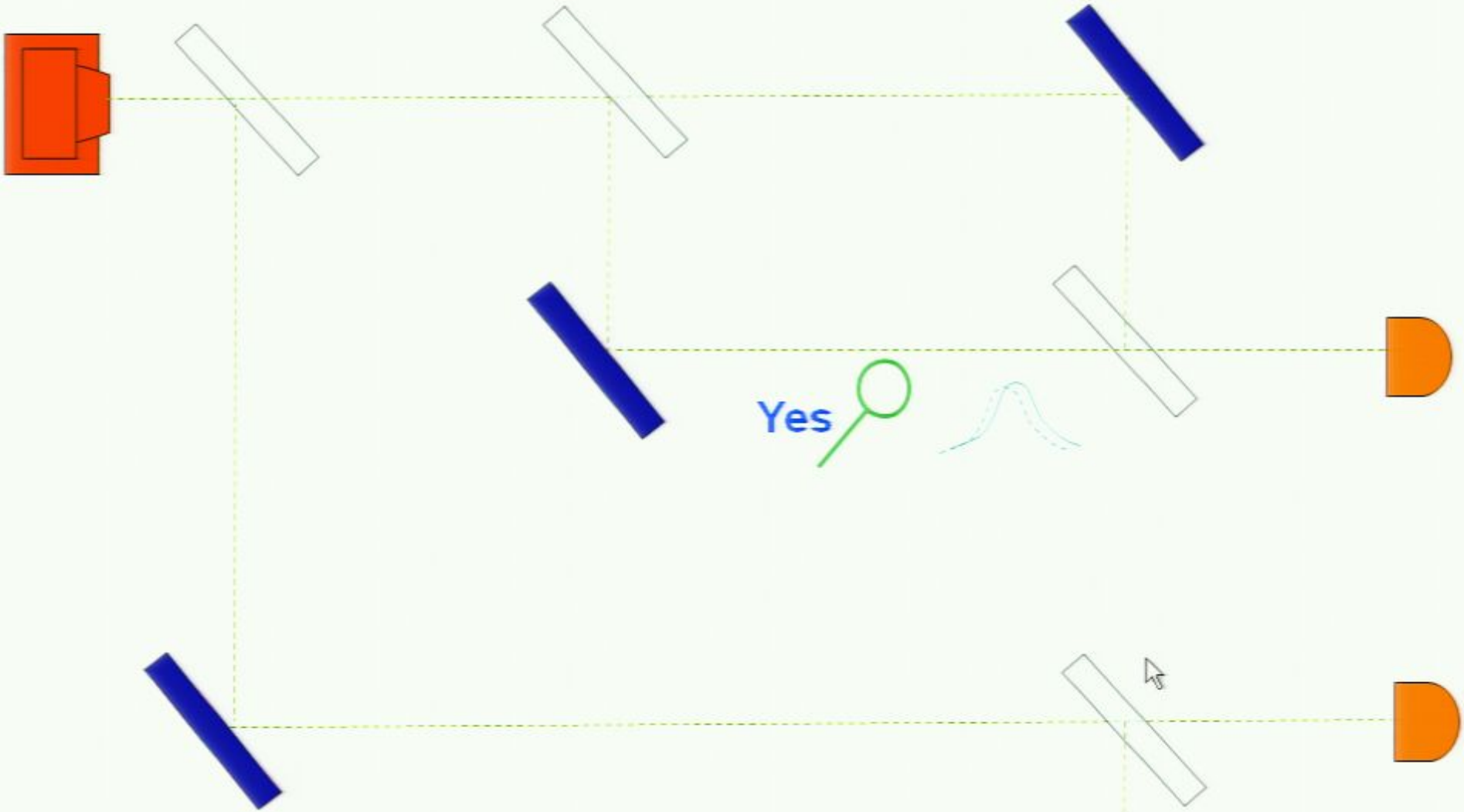

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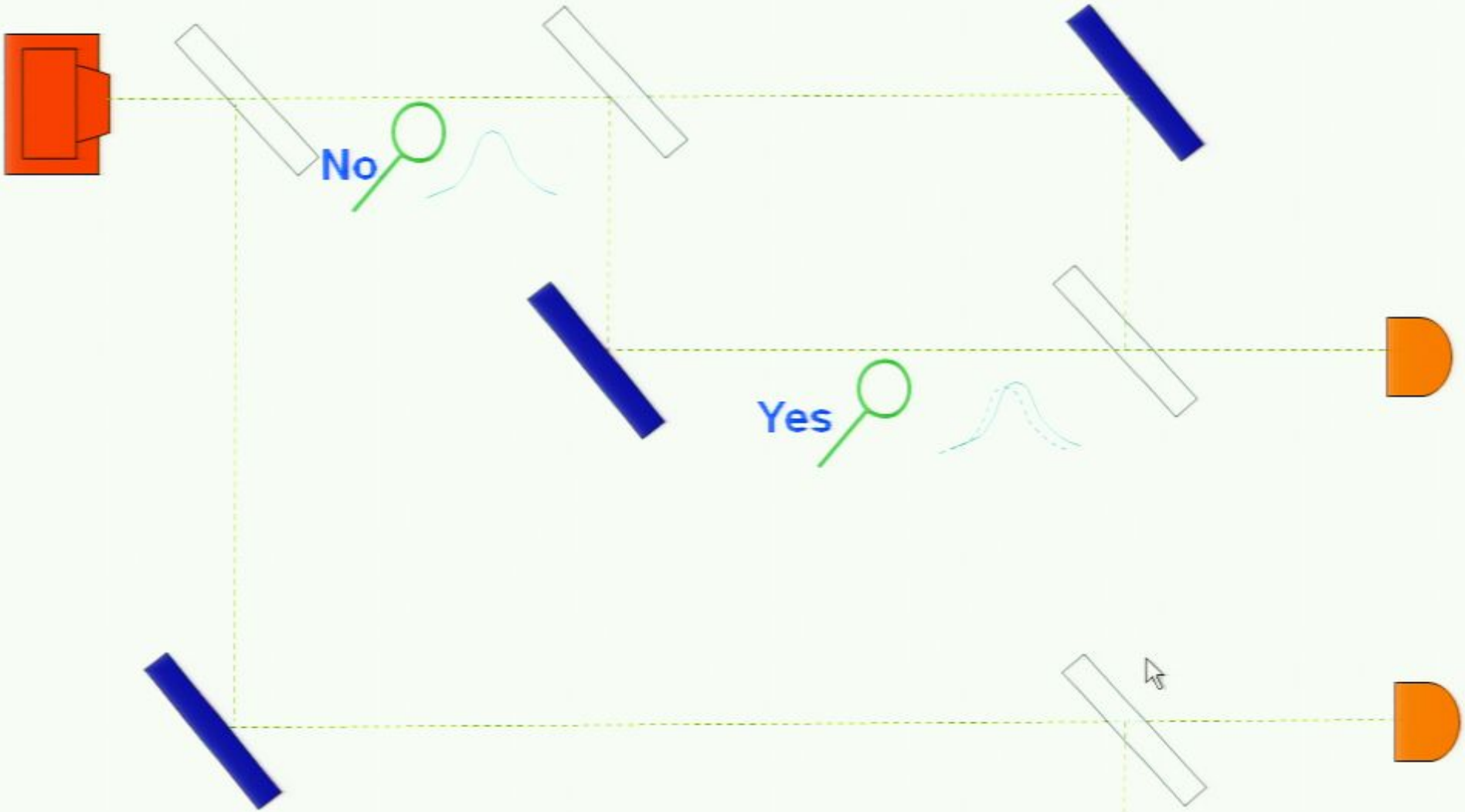

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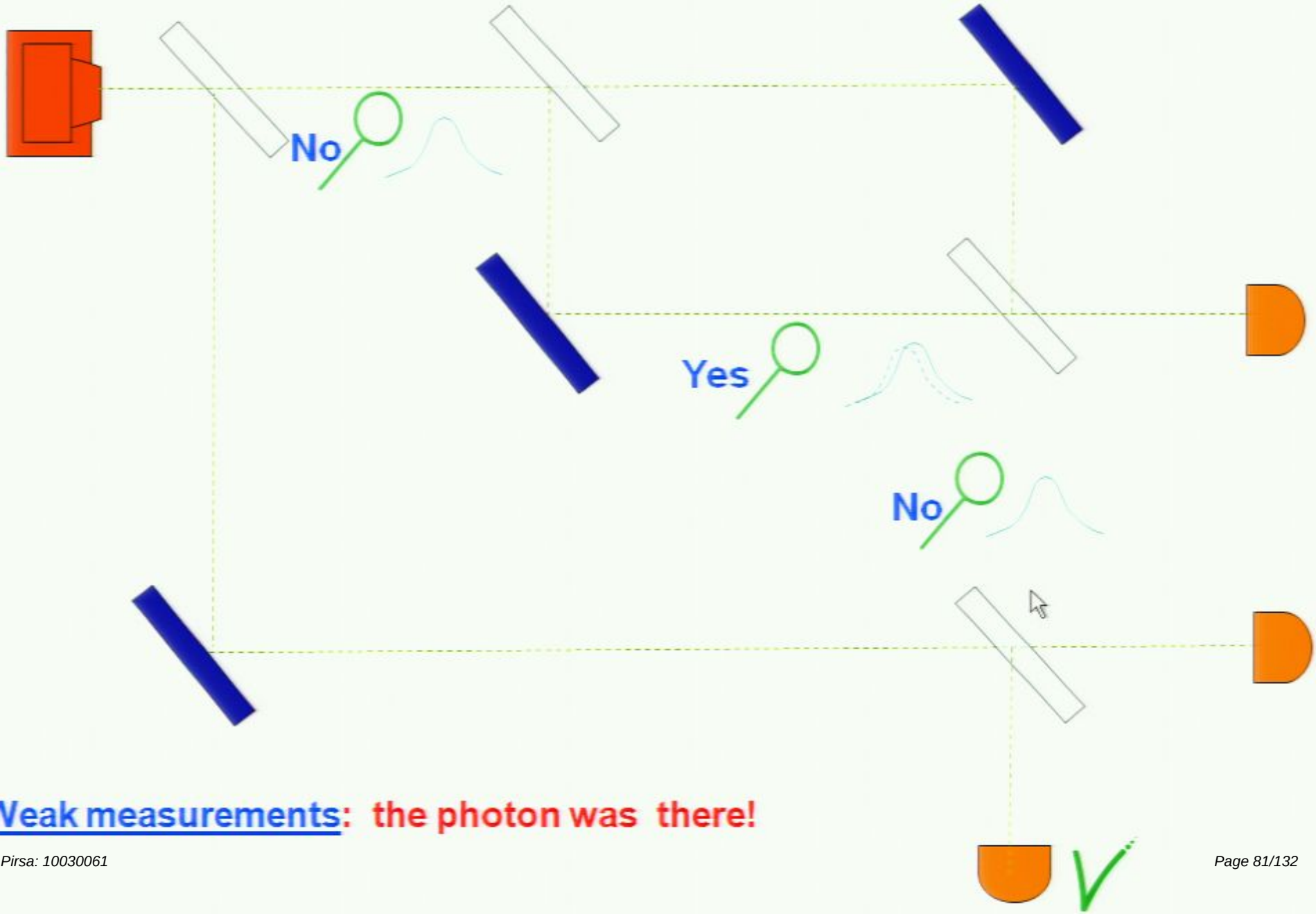

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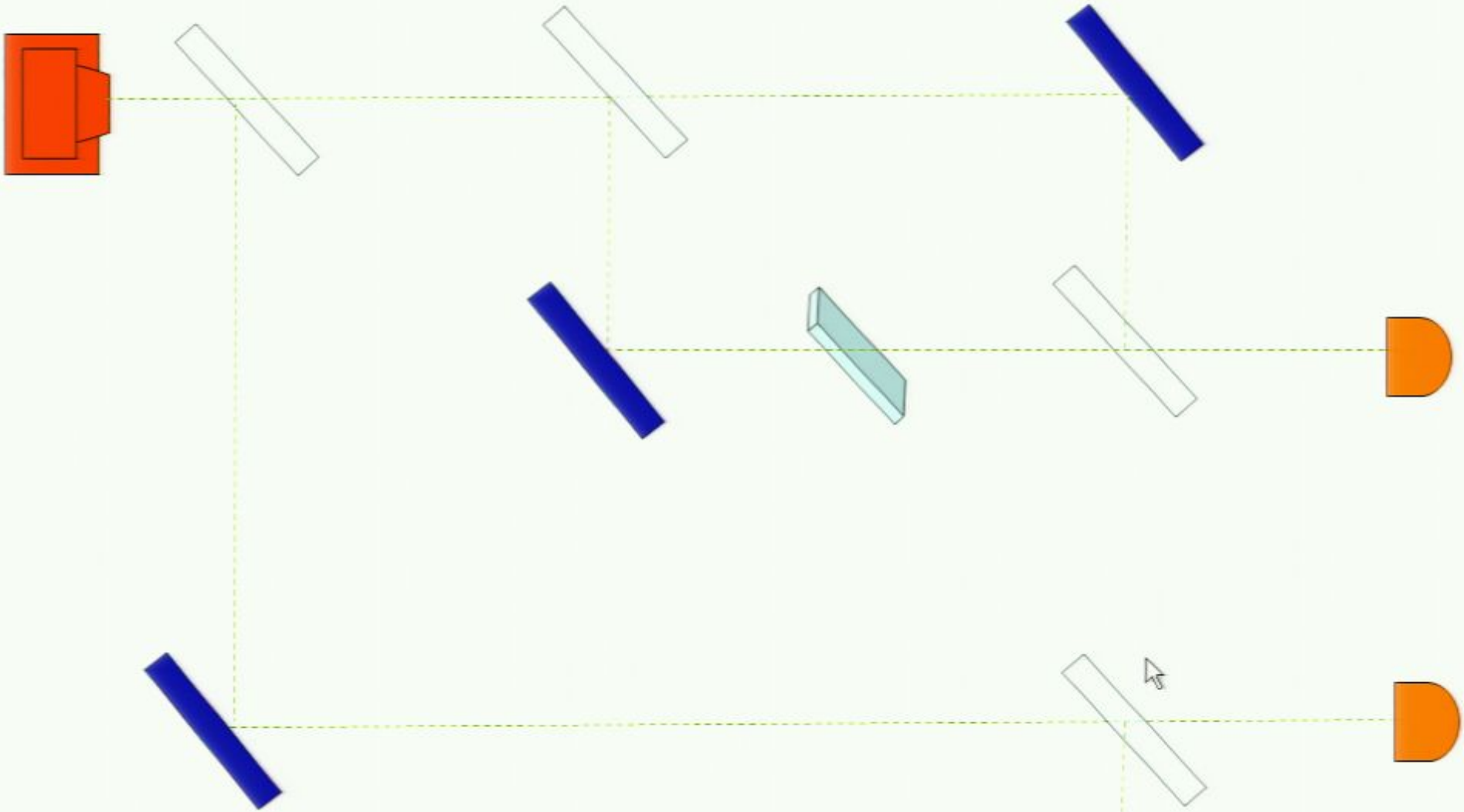

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But it was not on the path which leads towards it!

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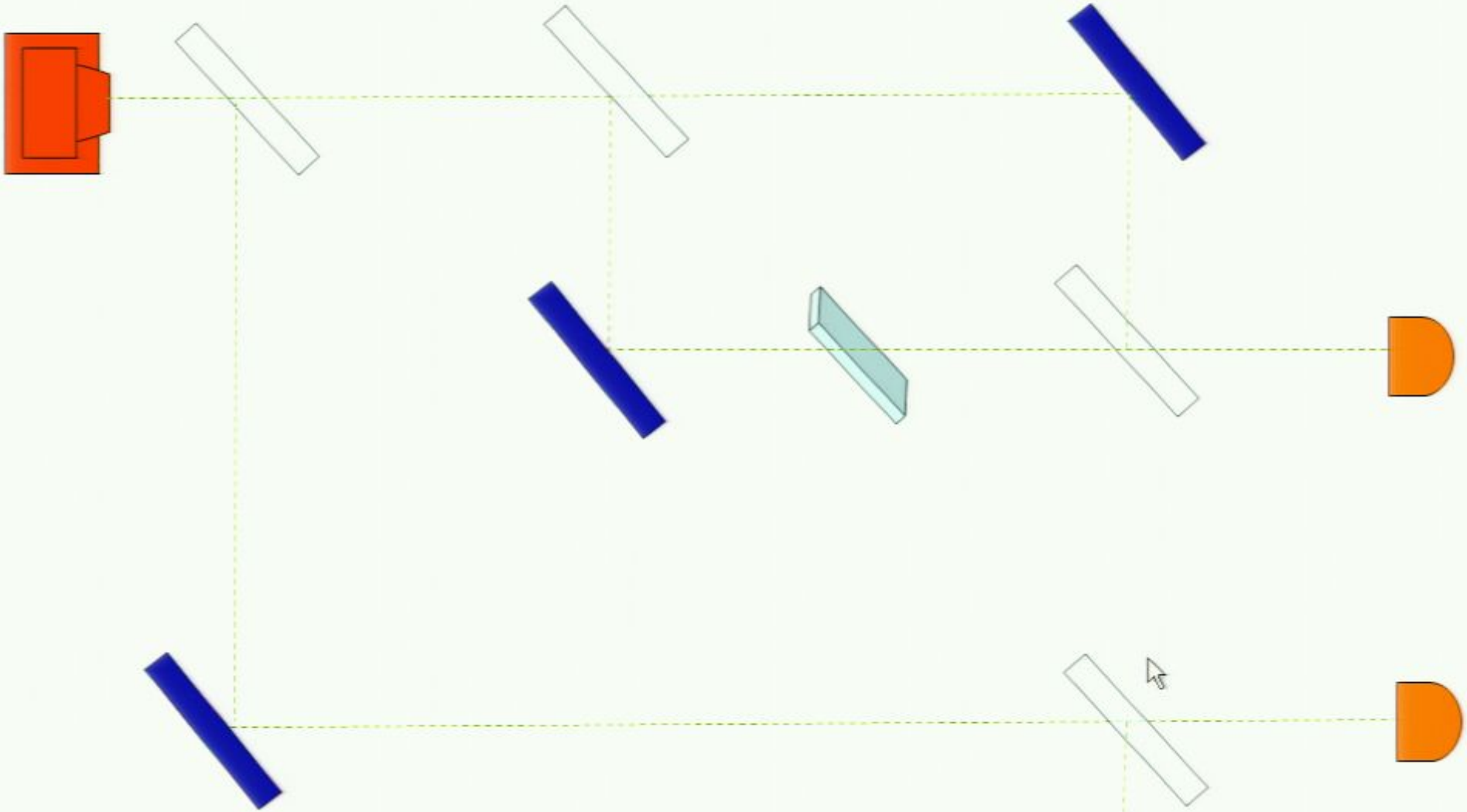

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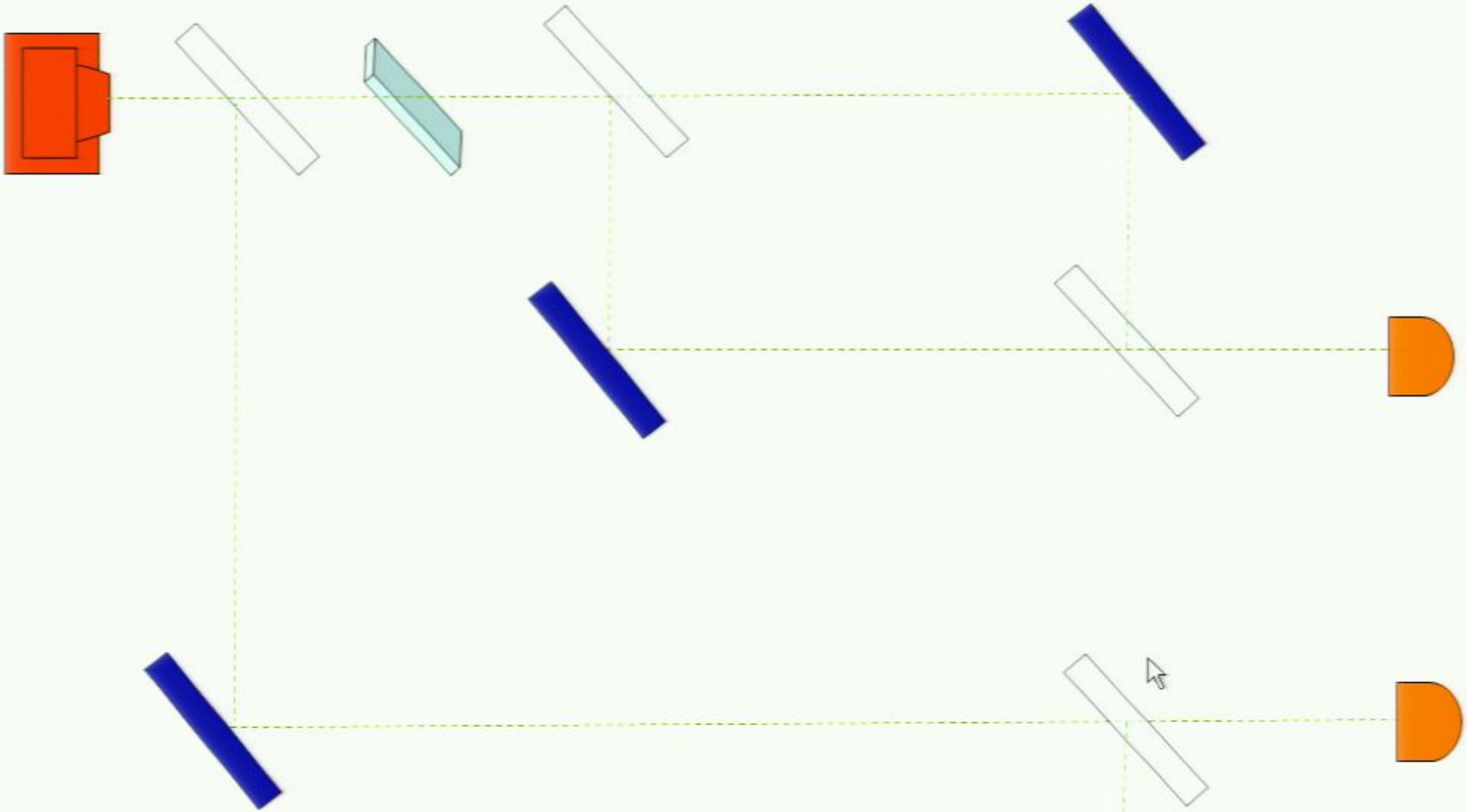

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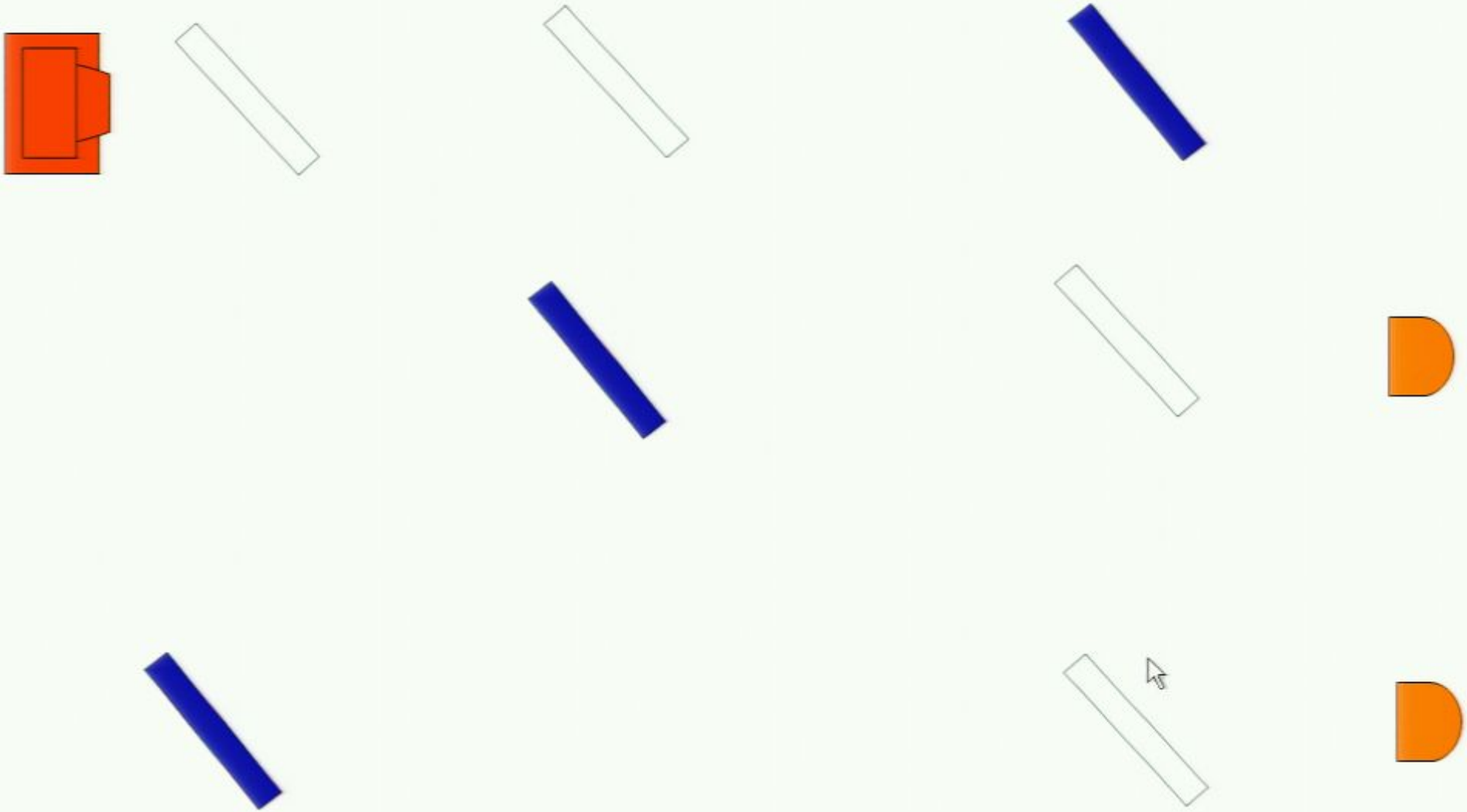

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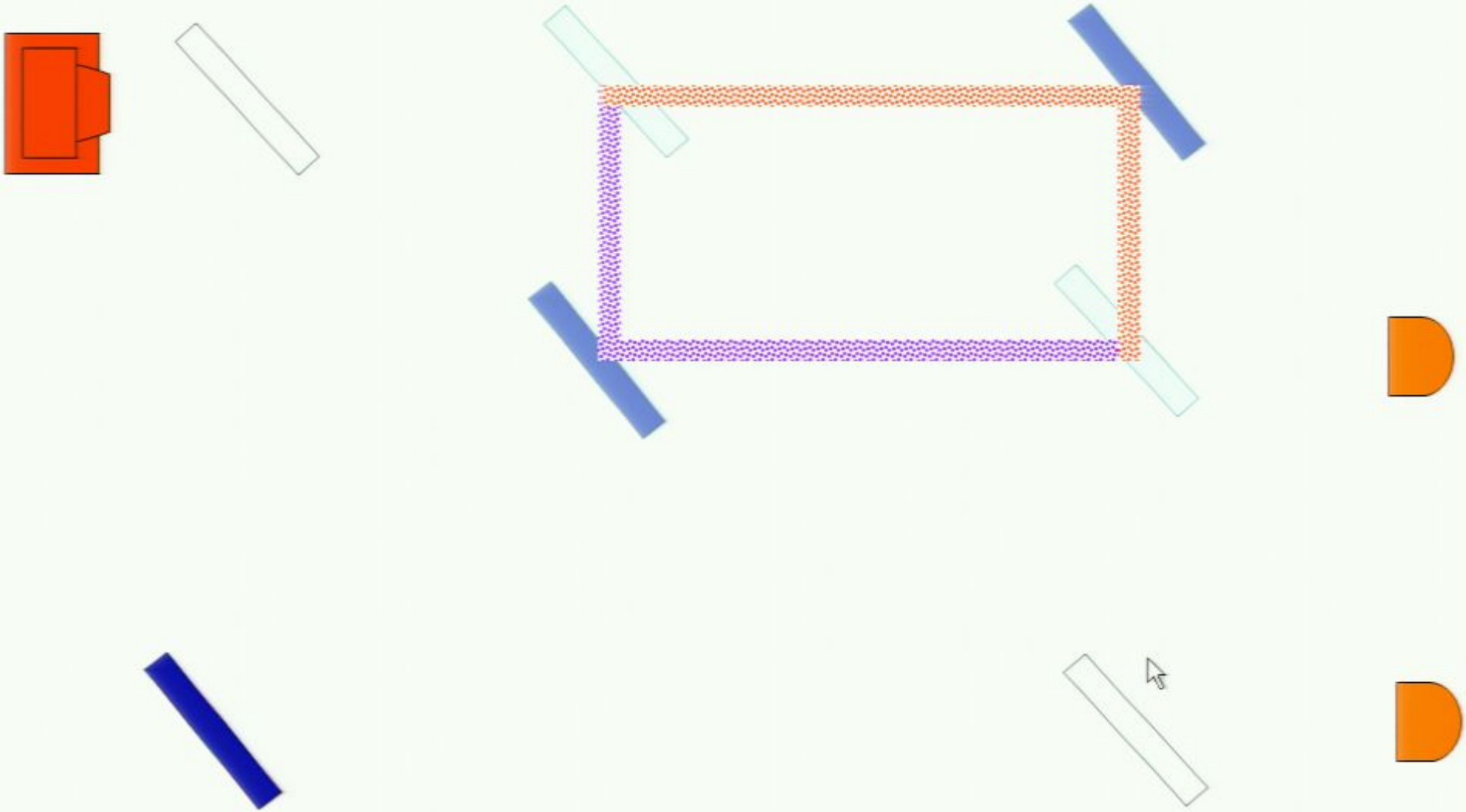

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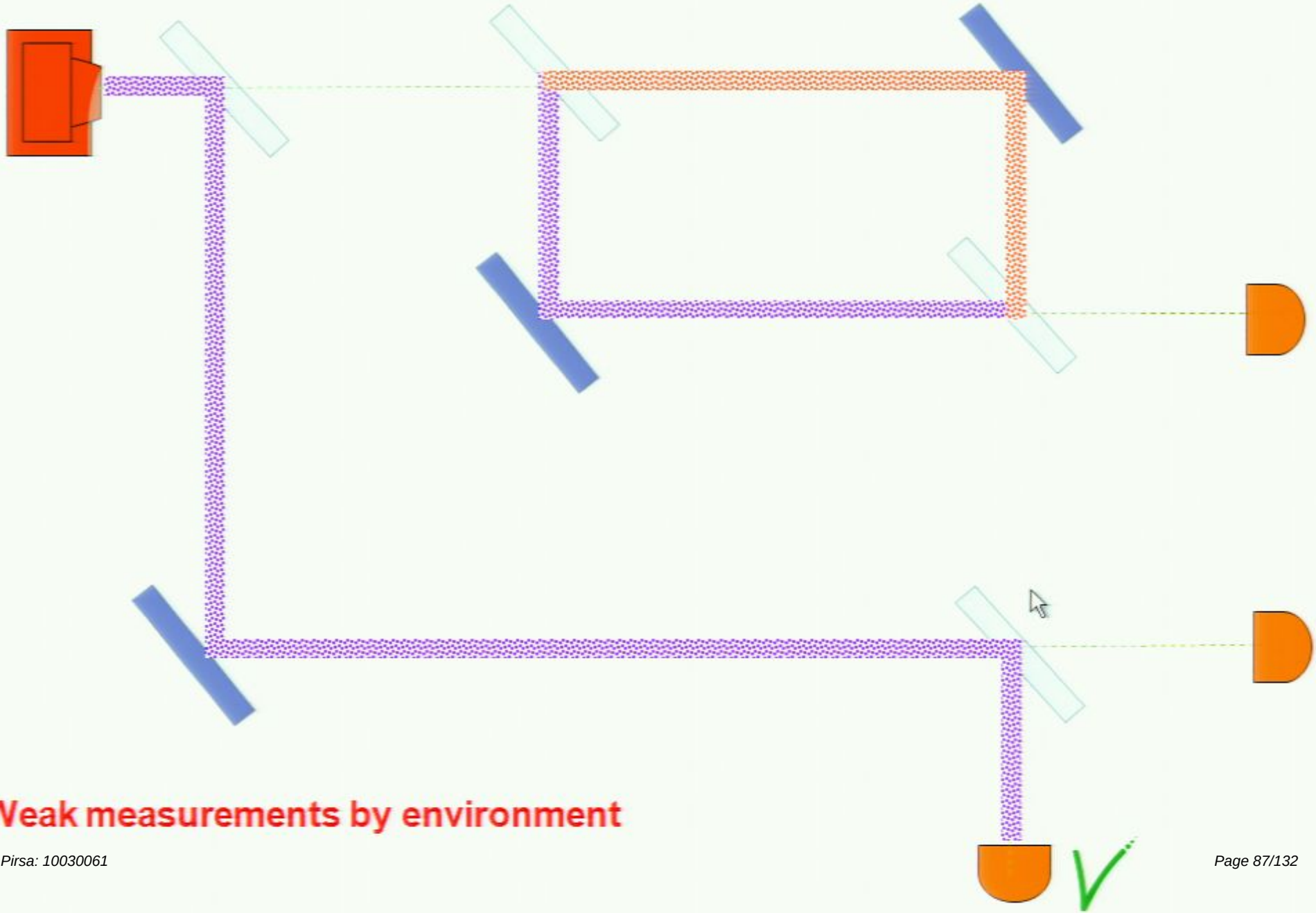

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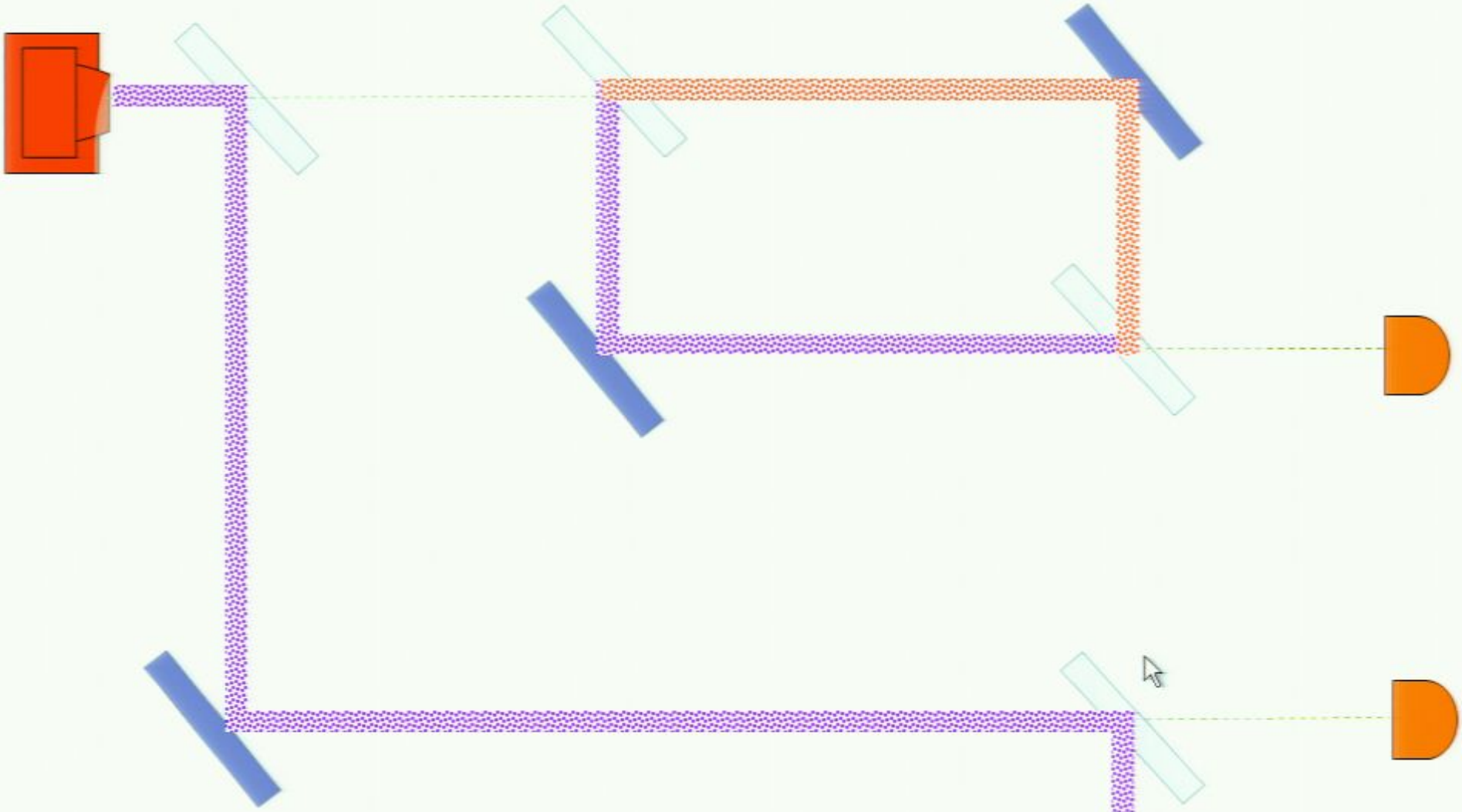

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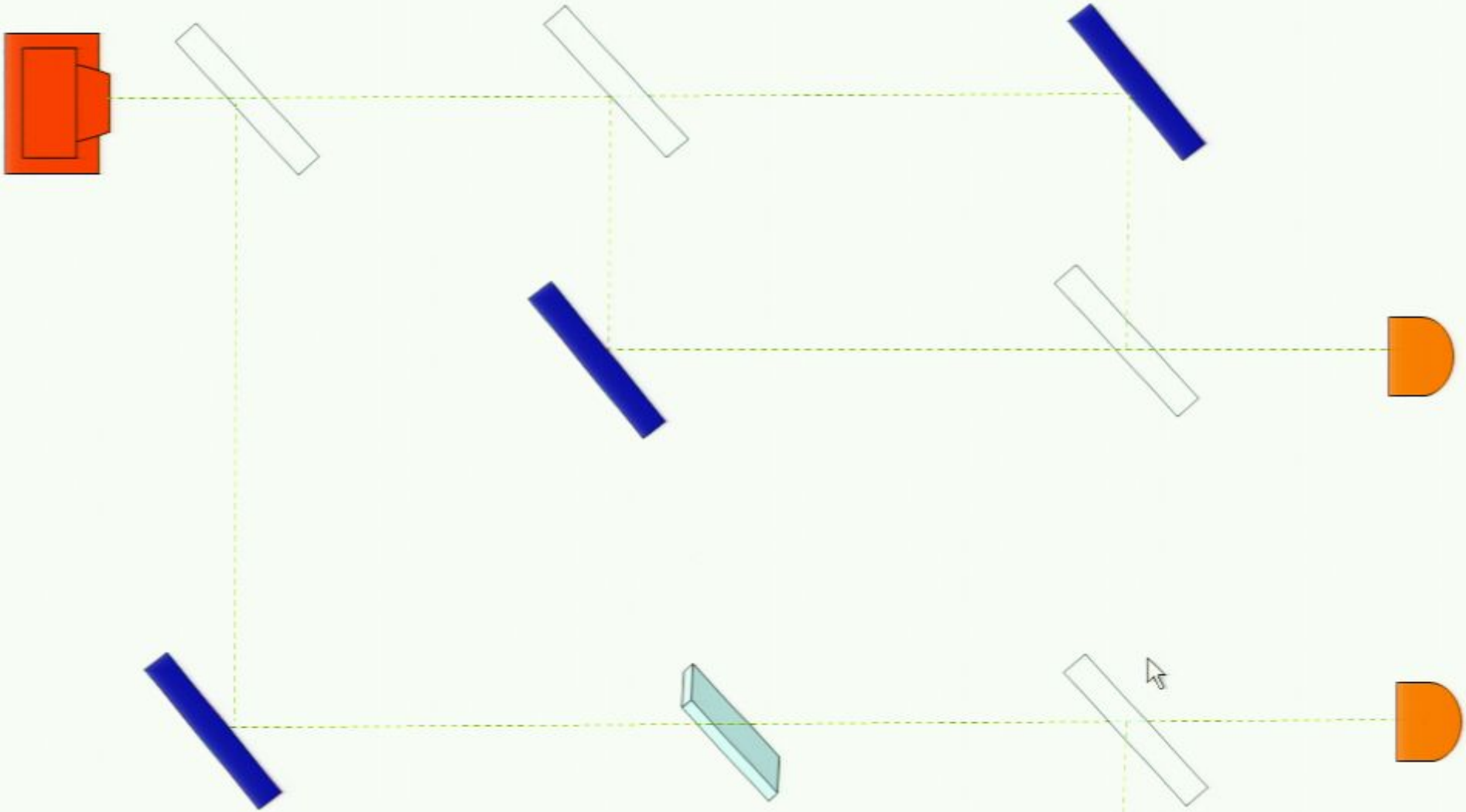

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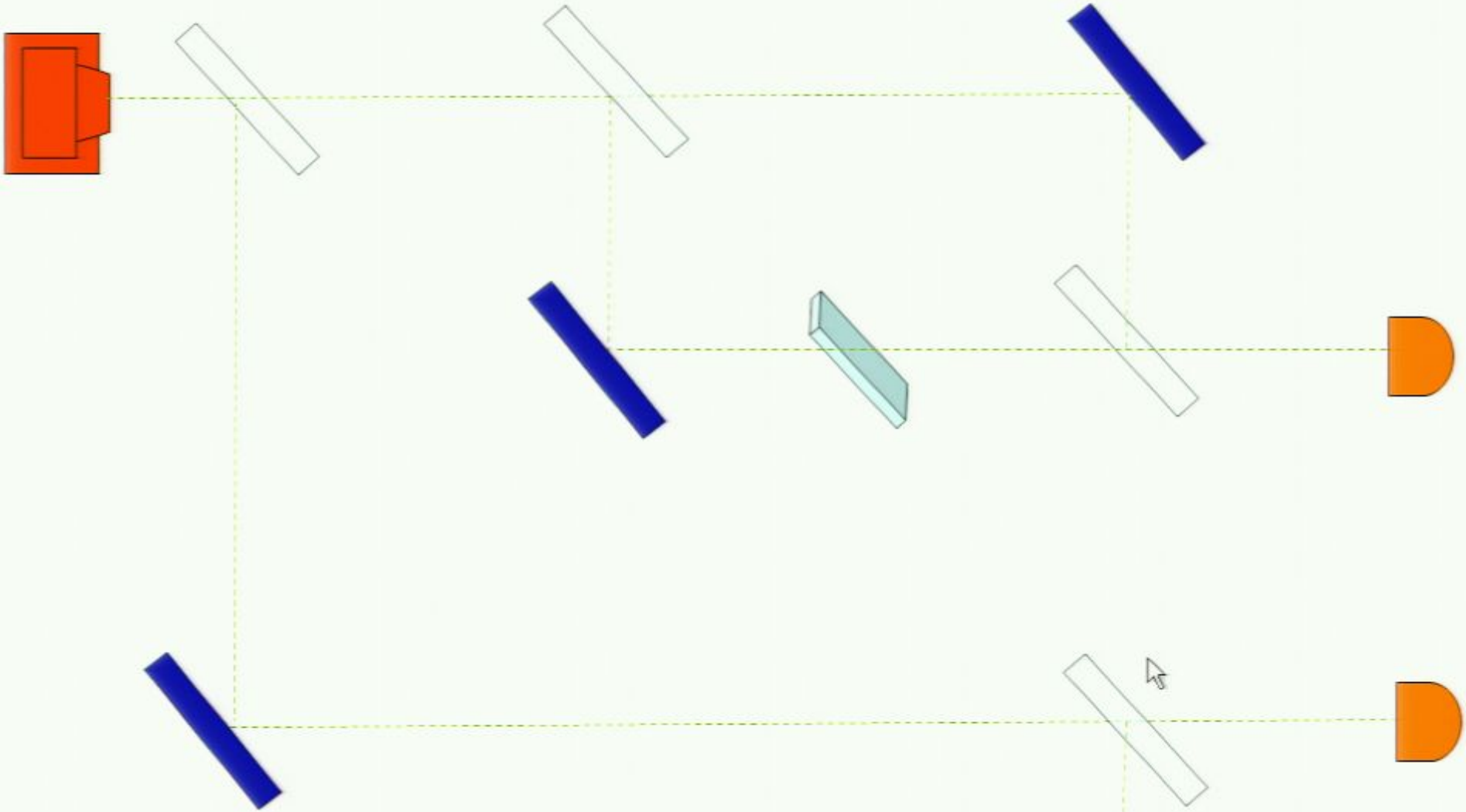

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The two-state vector formalism expalnation

The pre- and post-selected particle is described by the two-state vector

$$\langle \Phi | \quad | \Psi \rangle$$

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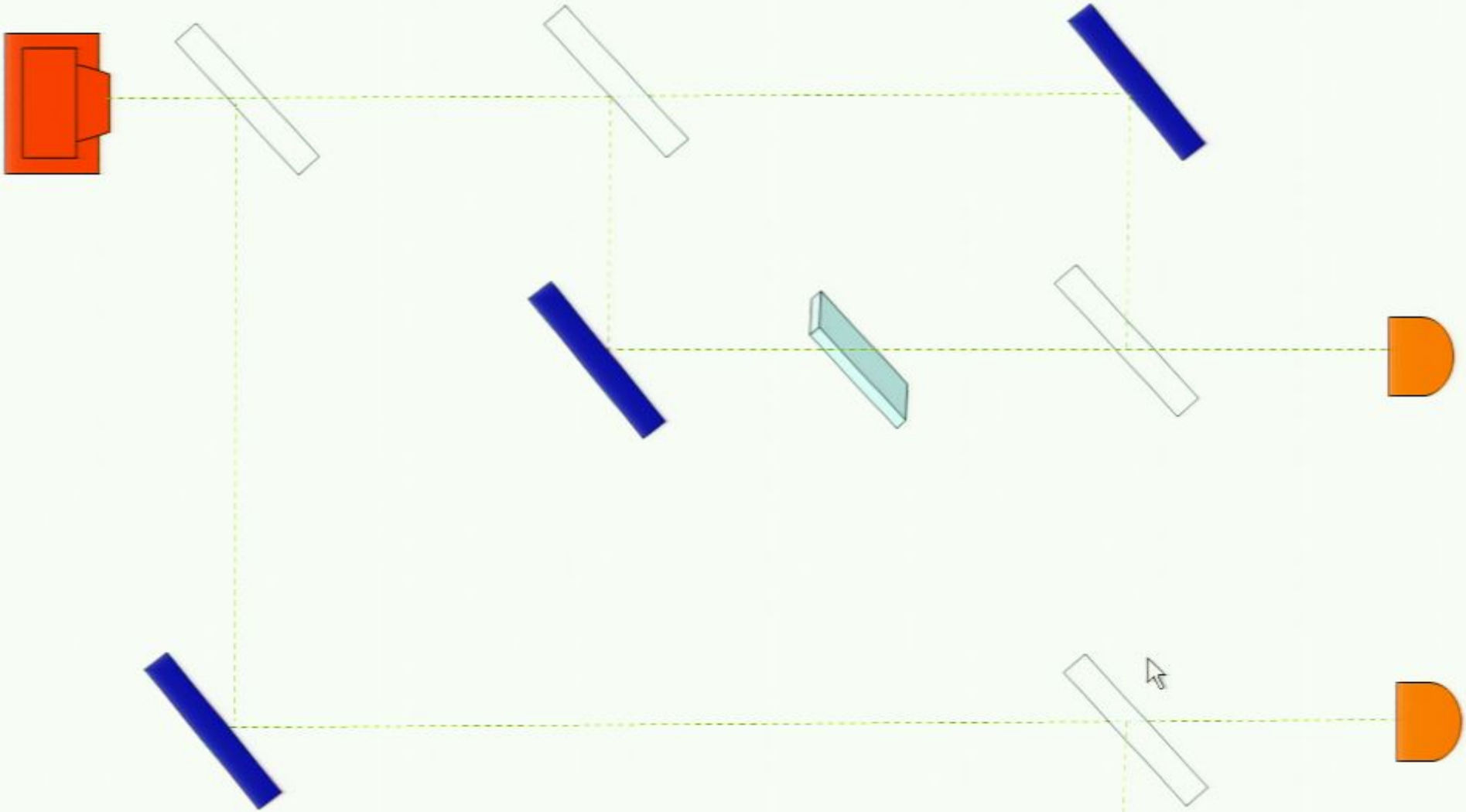

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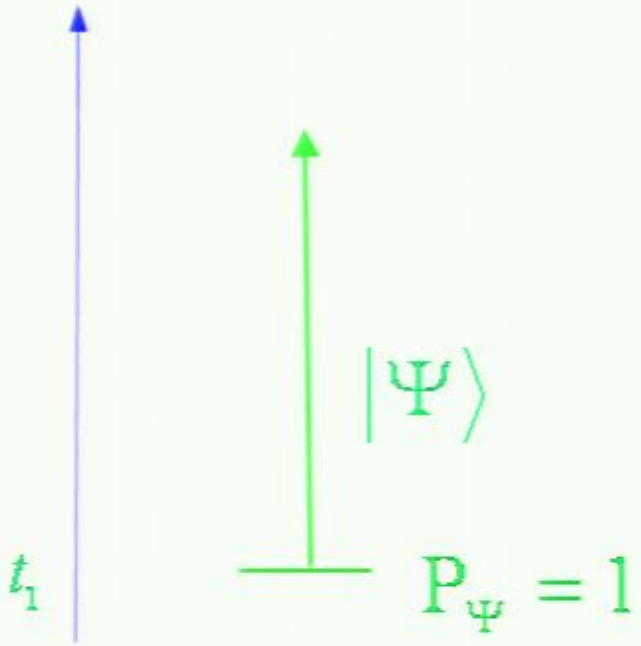

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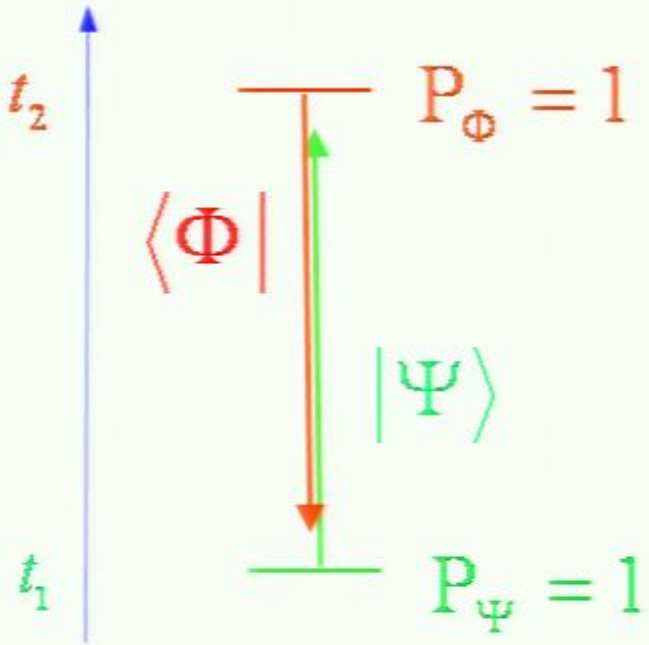

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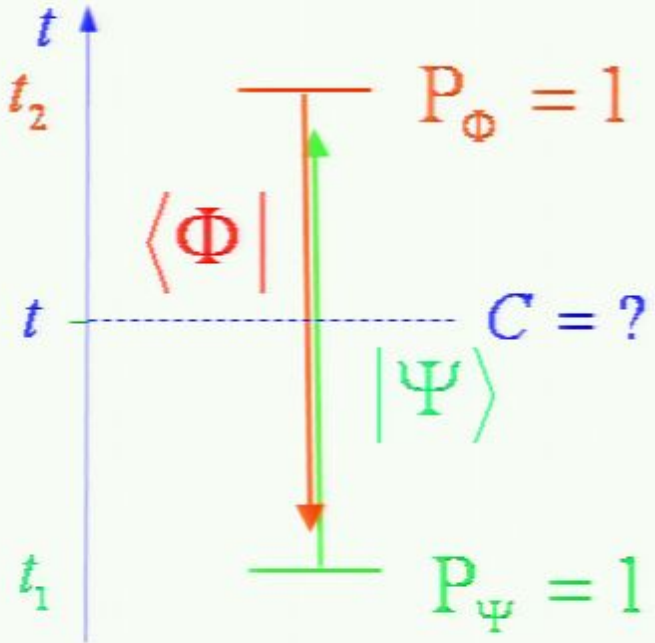

$$C_w \equiv \frac{\langle \Phi | C | \Psi \rangle}{\langle \Phi | \Psi \rangle}$$

The outcomes of weak measurements are weak values

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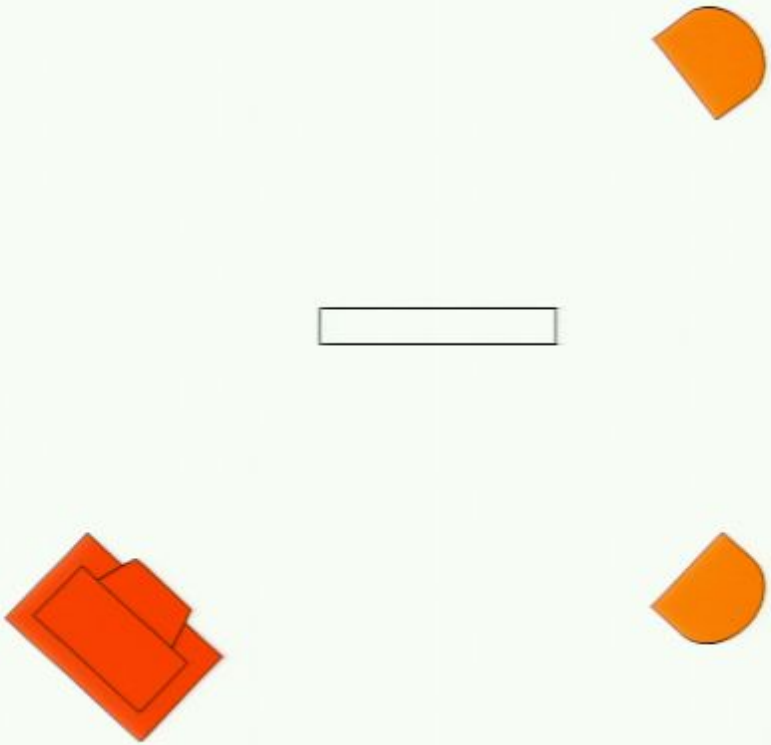

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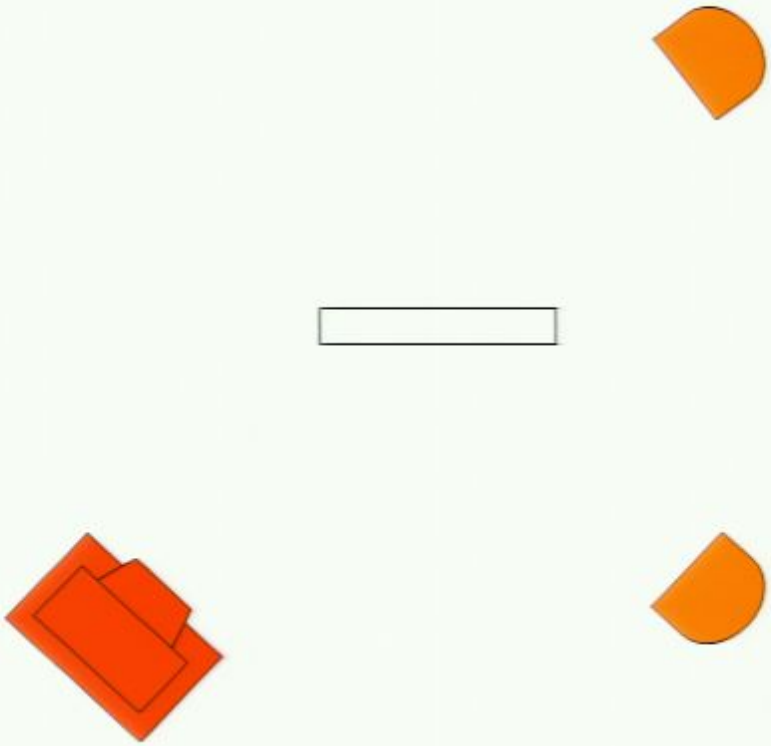
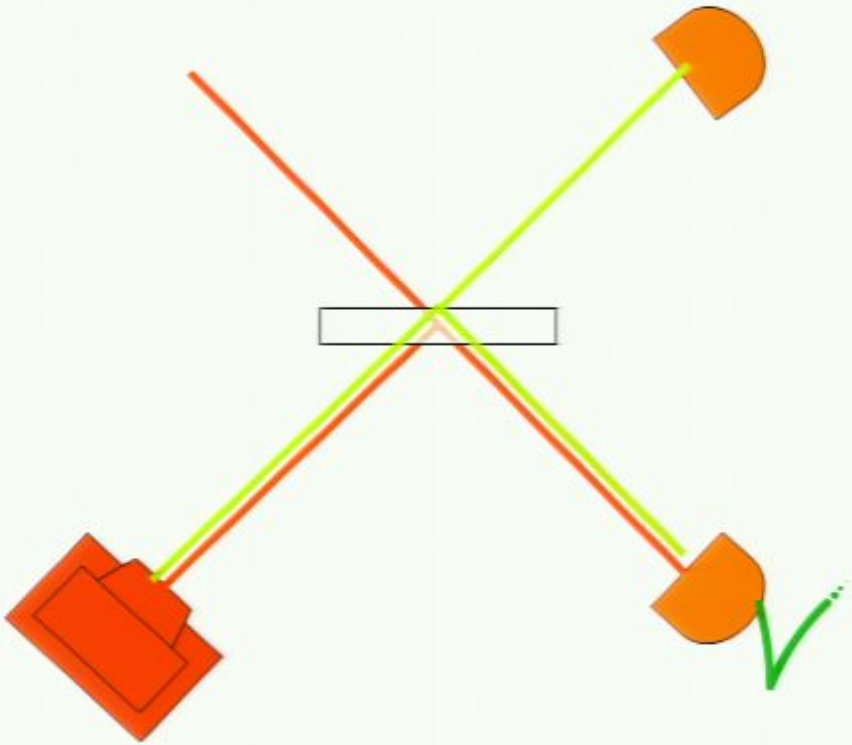


Where Is the Quantum Particle between Two Measurements?



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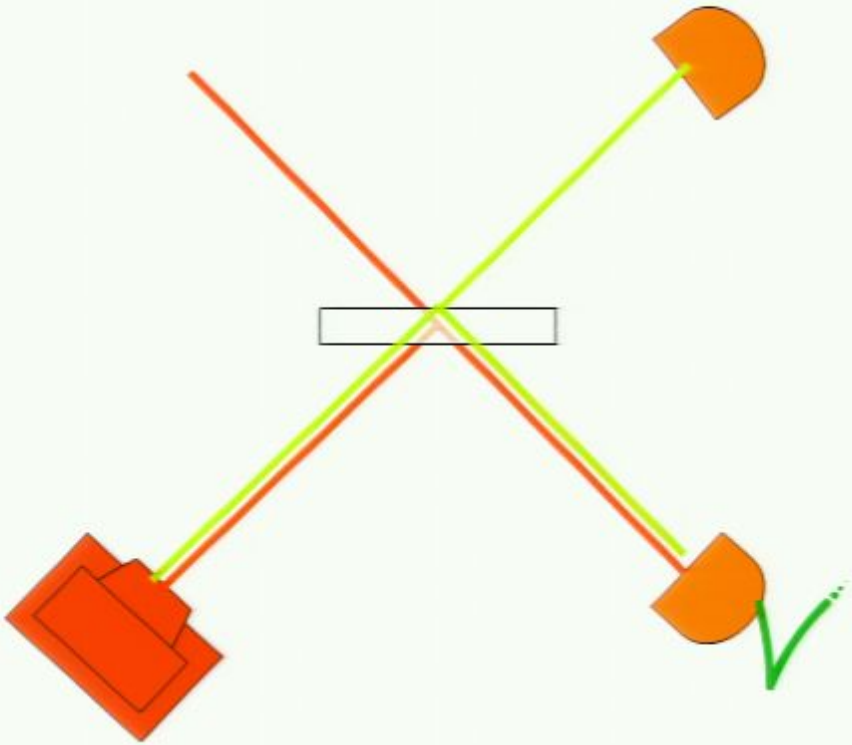

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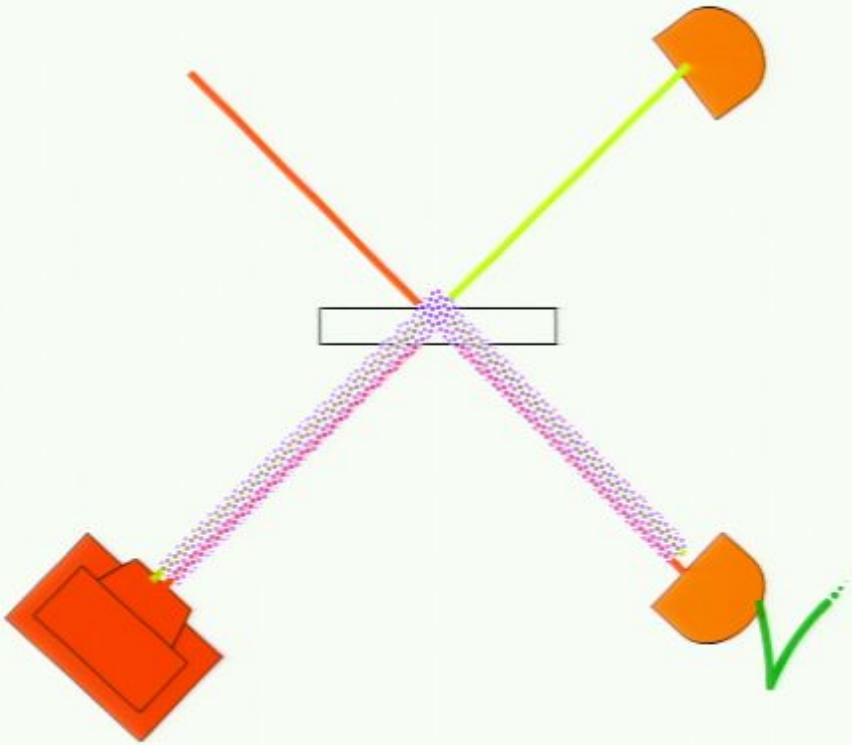

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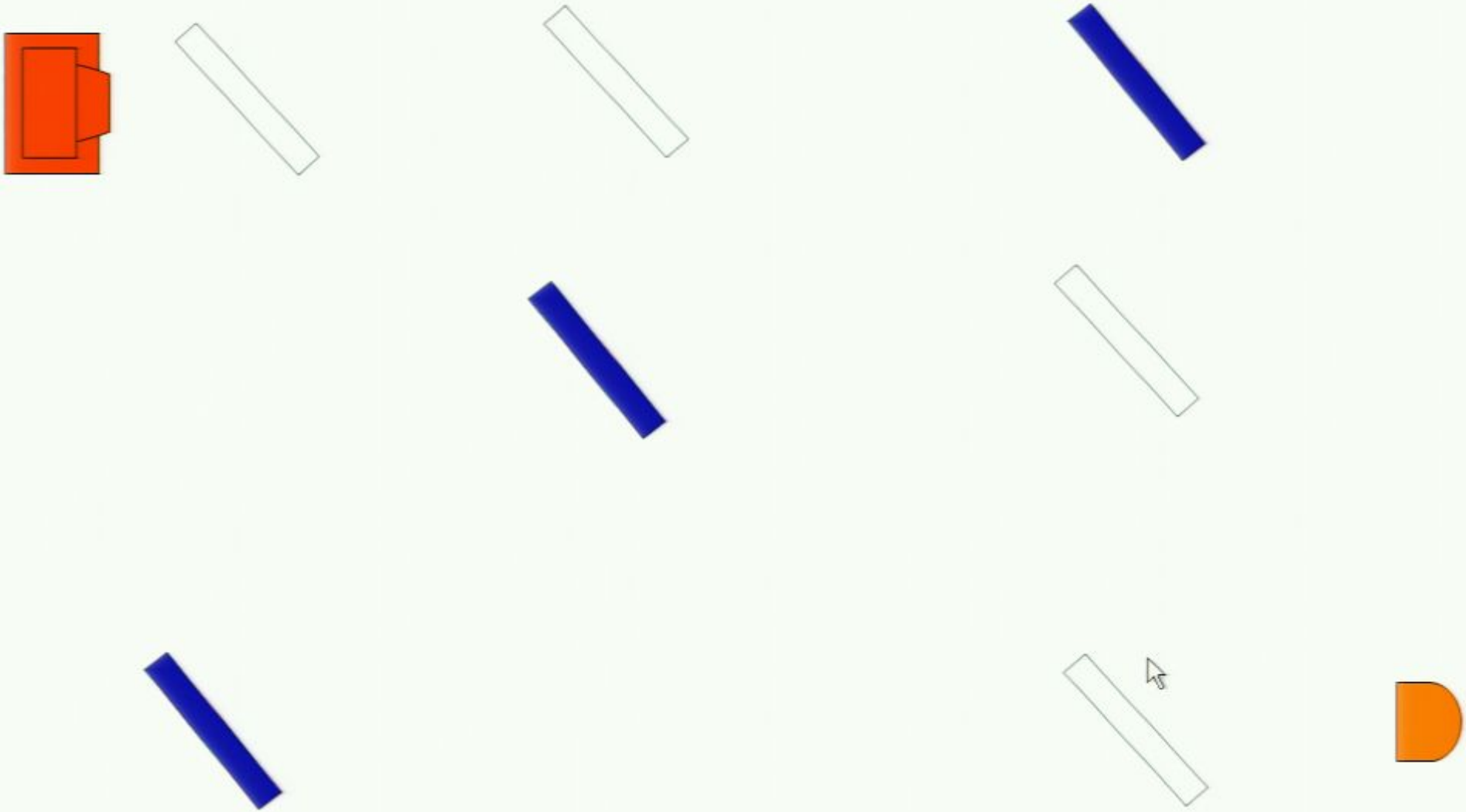

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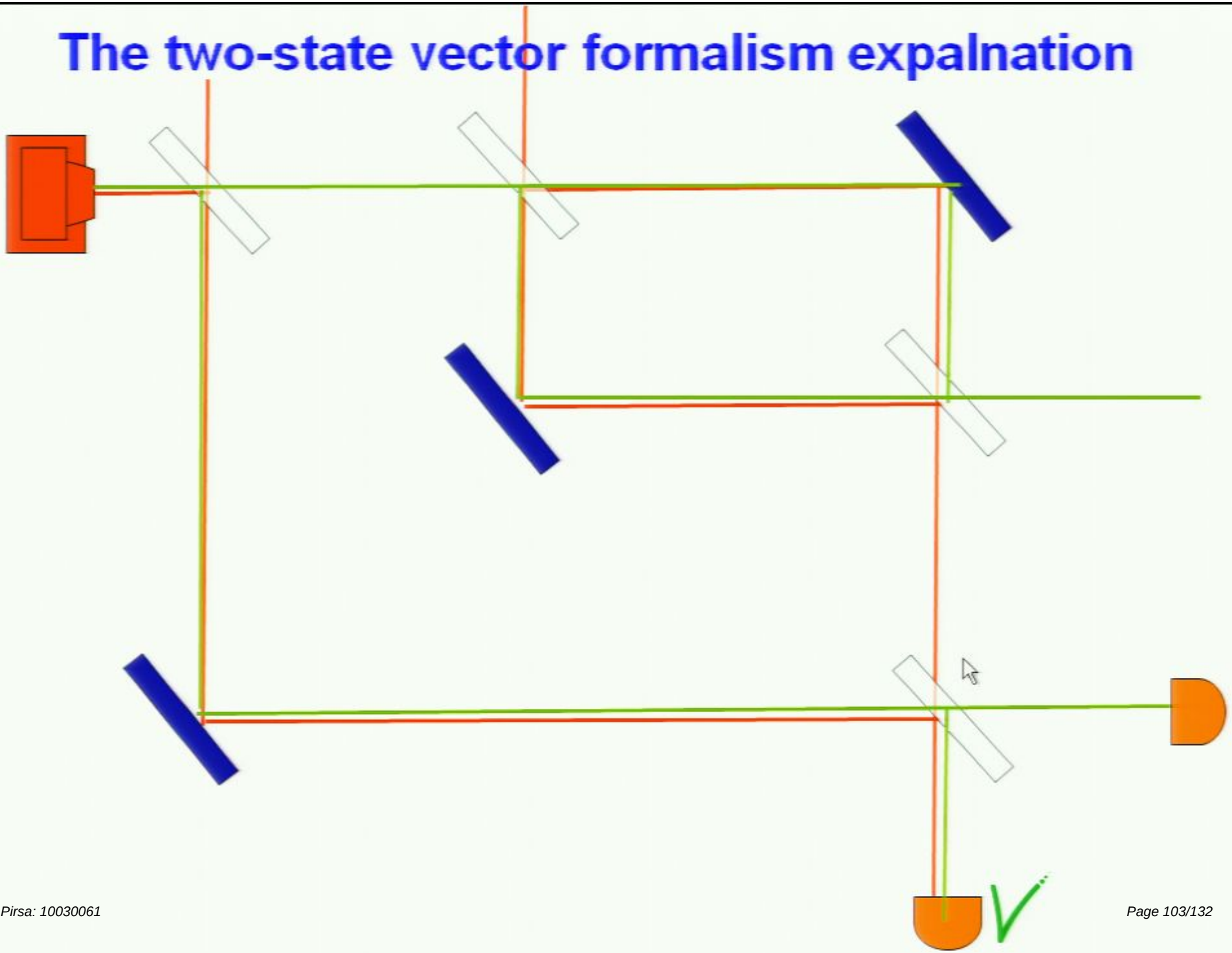

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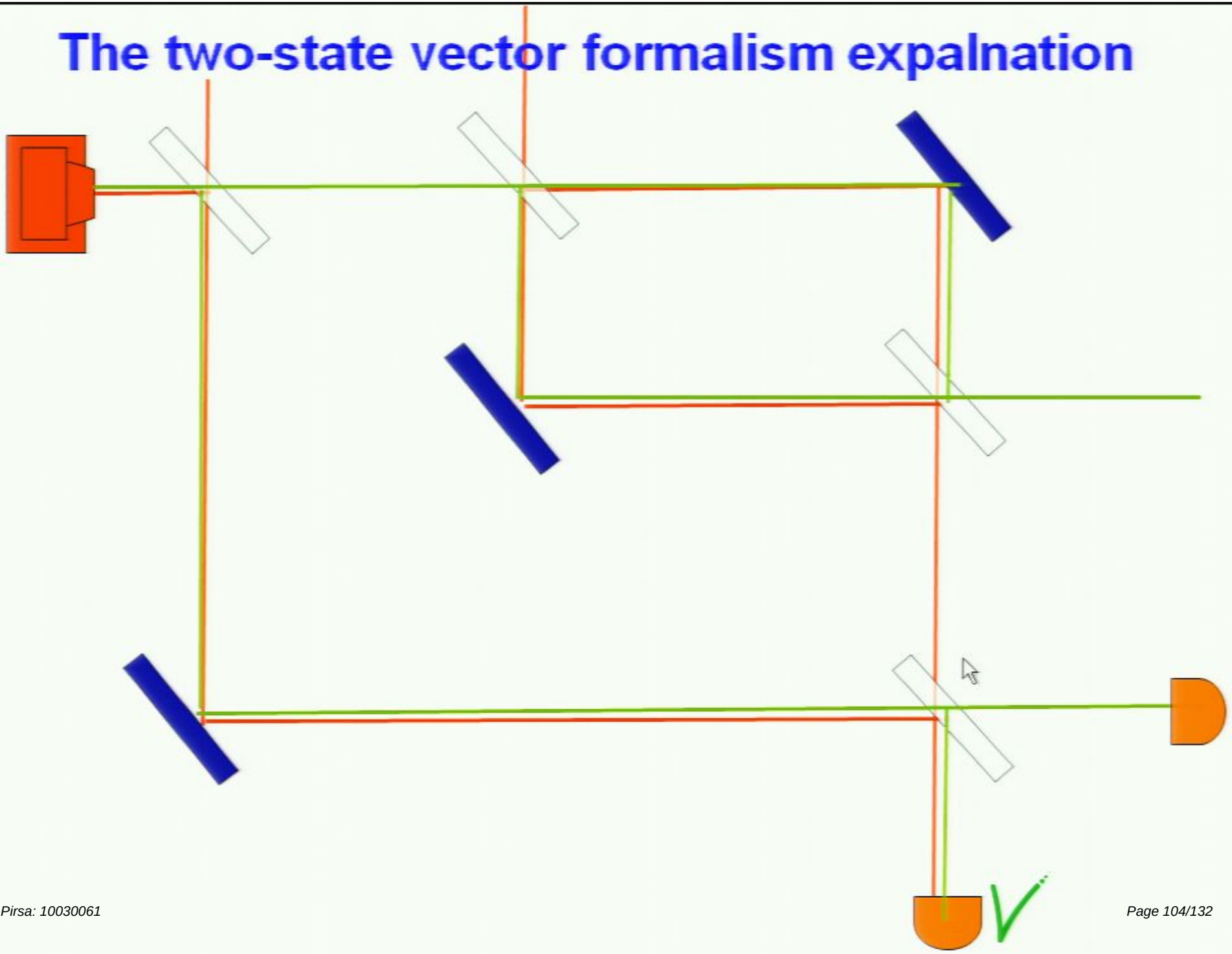

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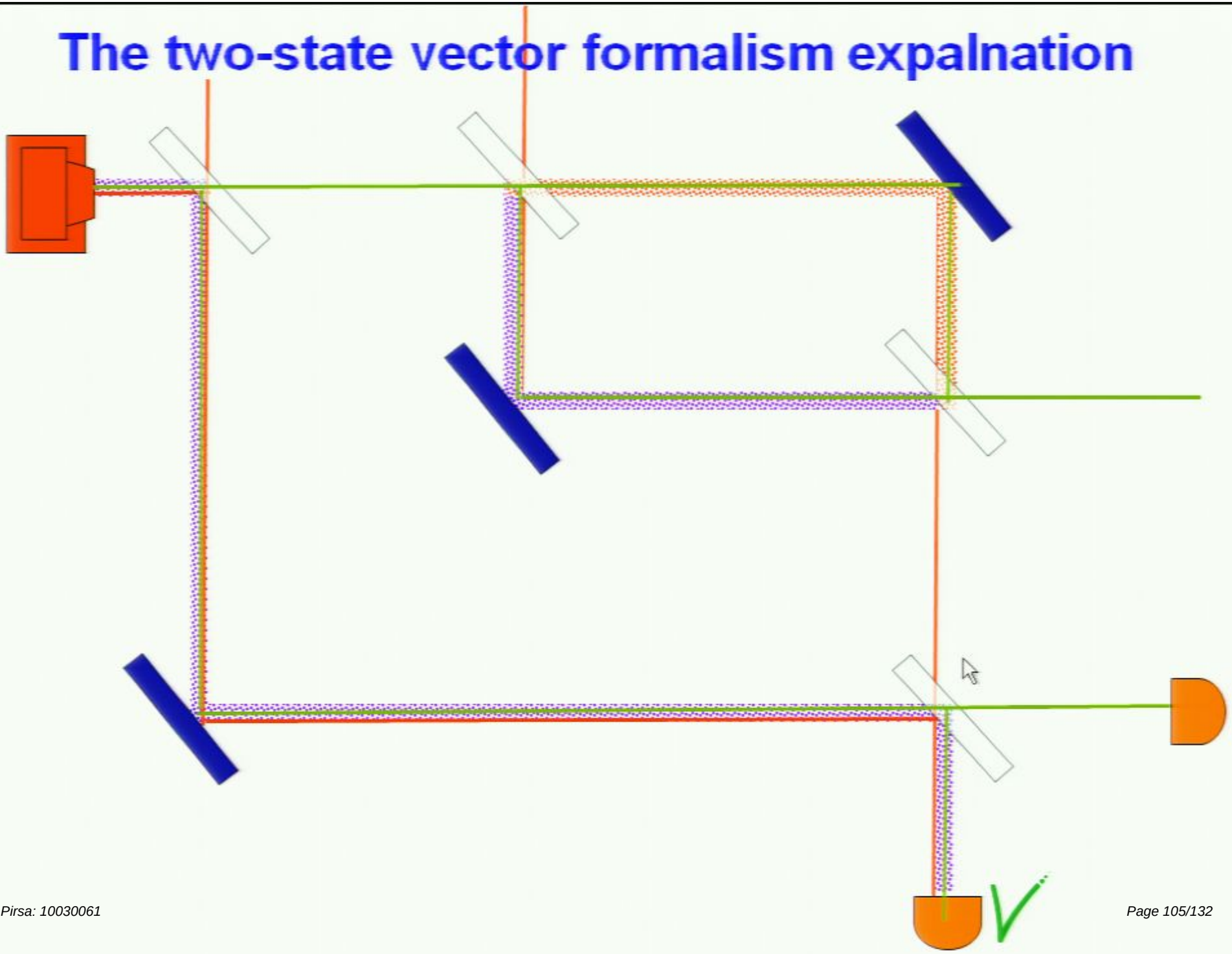

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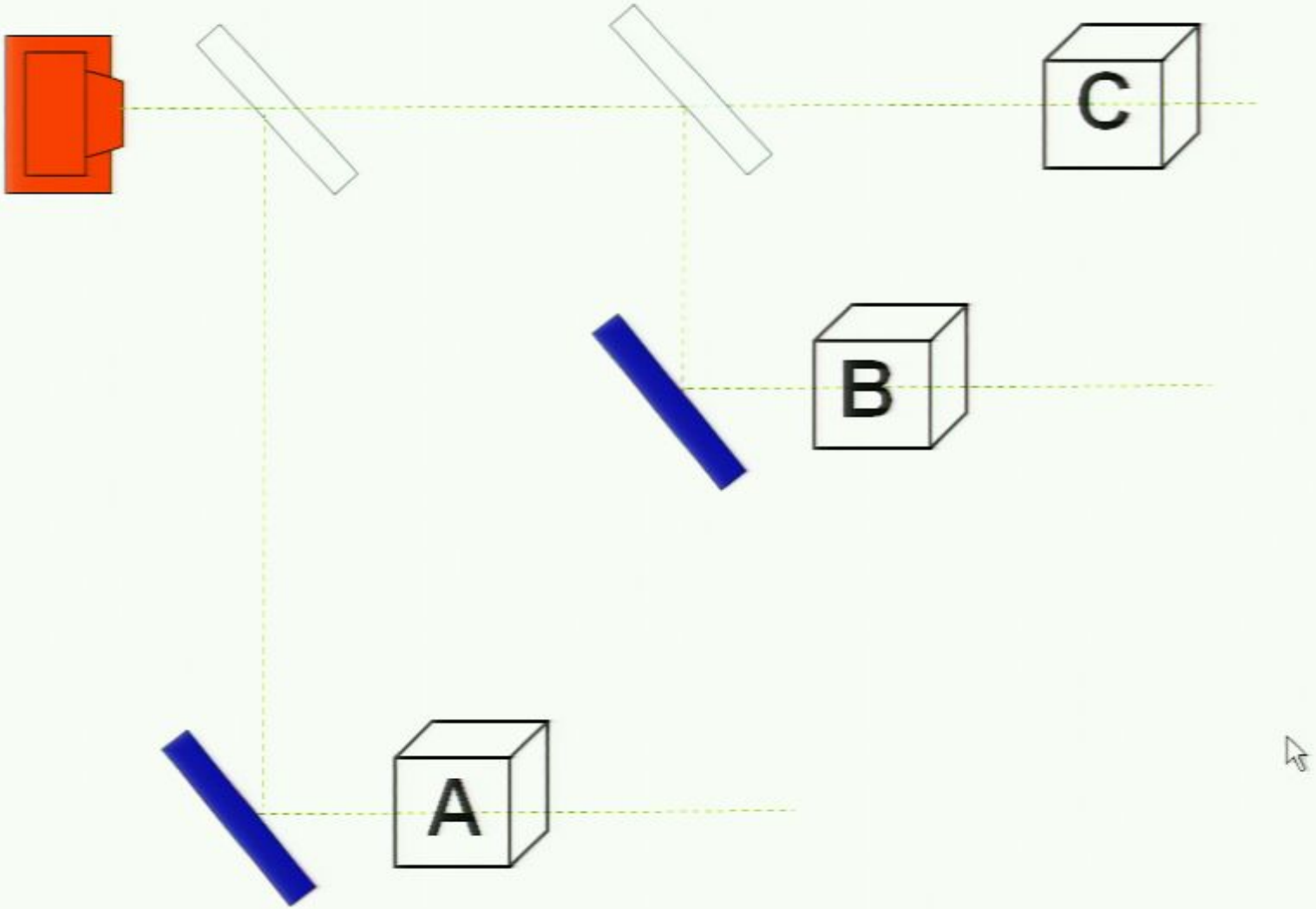

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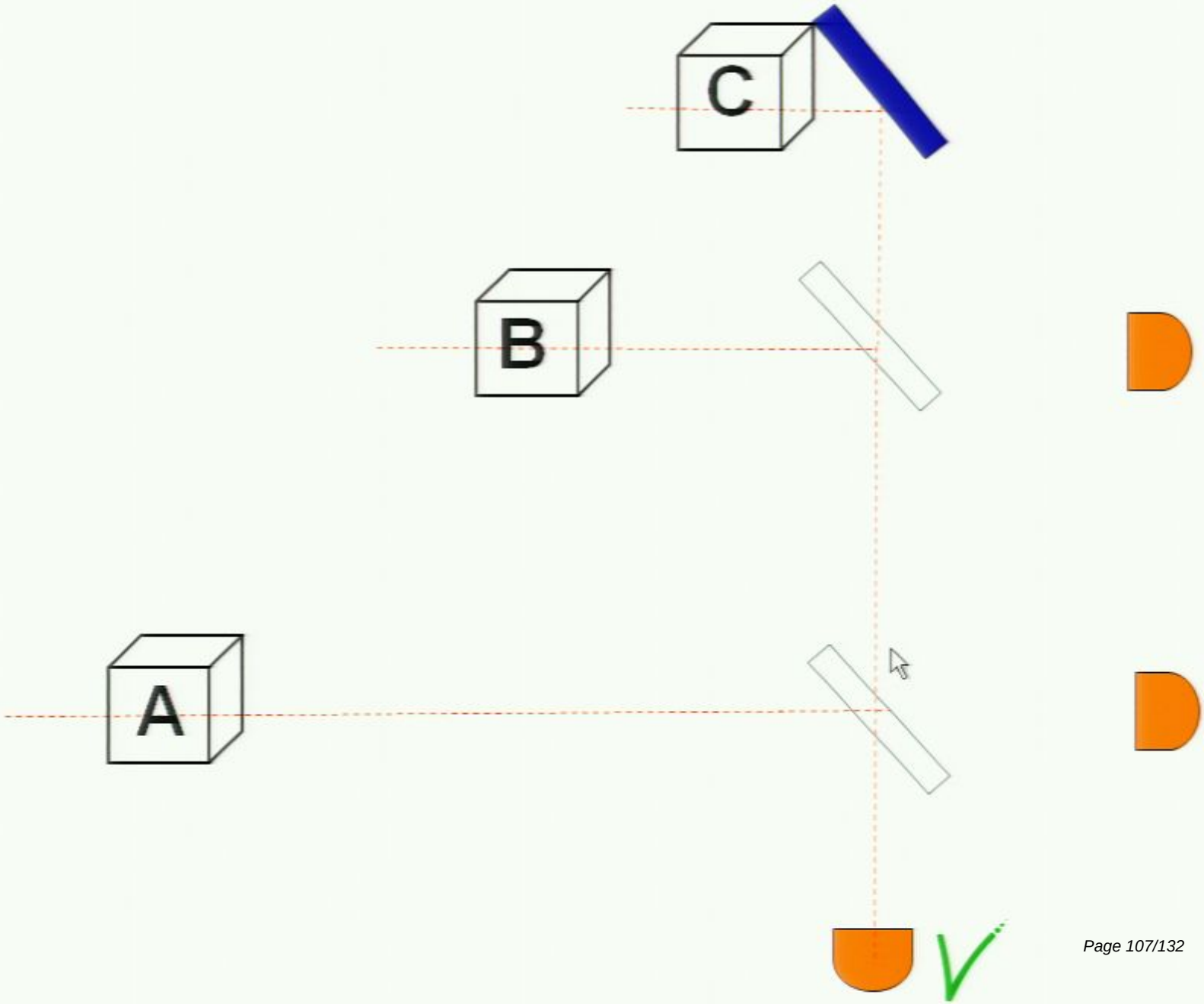

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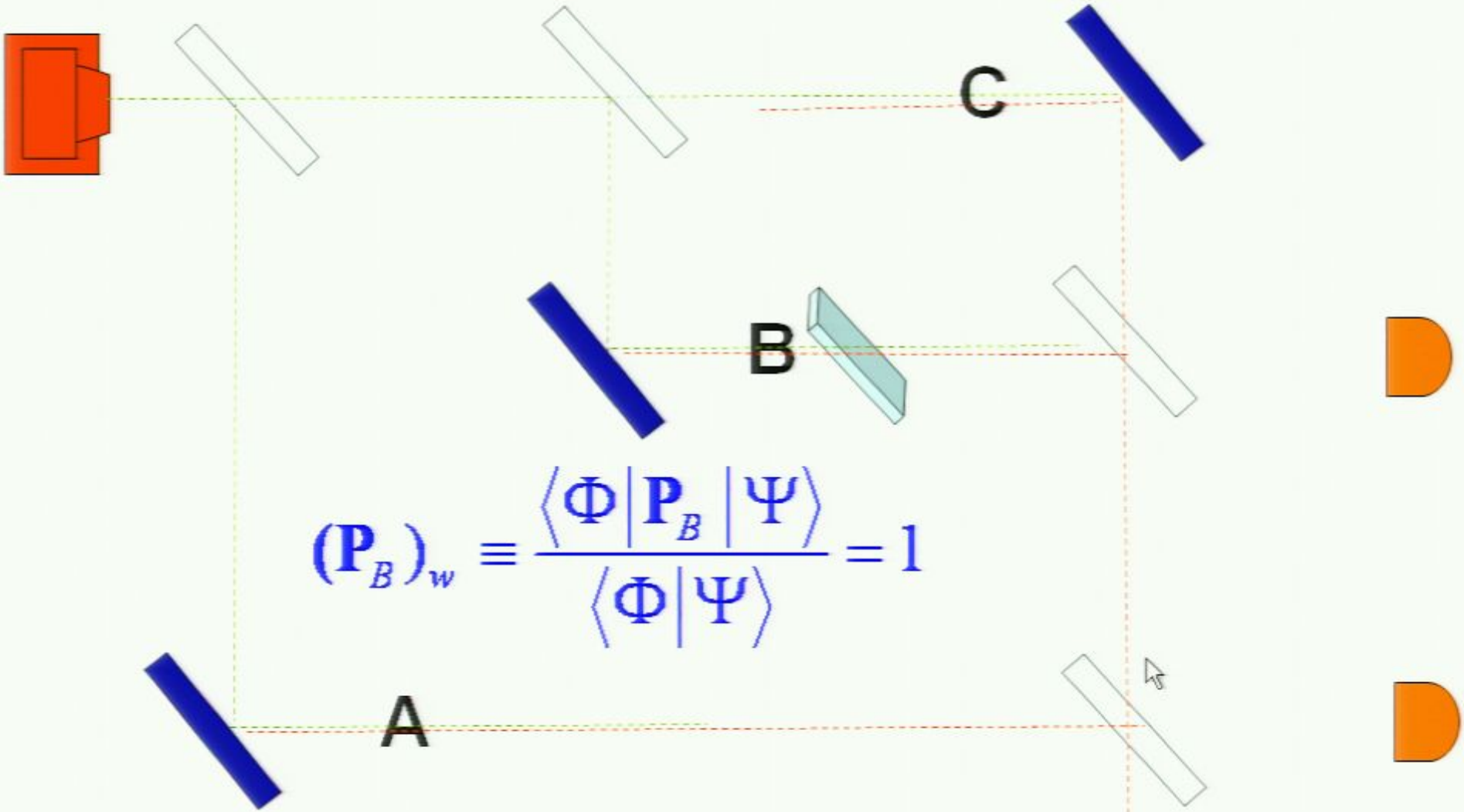

$$(\mathbf{P}_B)_w \equiv \frac{\langle \Phi | \mathbf{P}_B | \Psi \rangle}{\langle \Phi | \Psi \rangle} = 1$$

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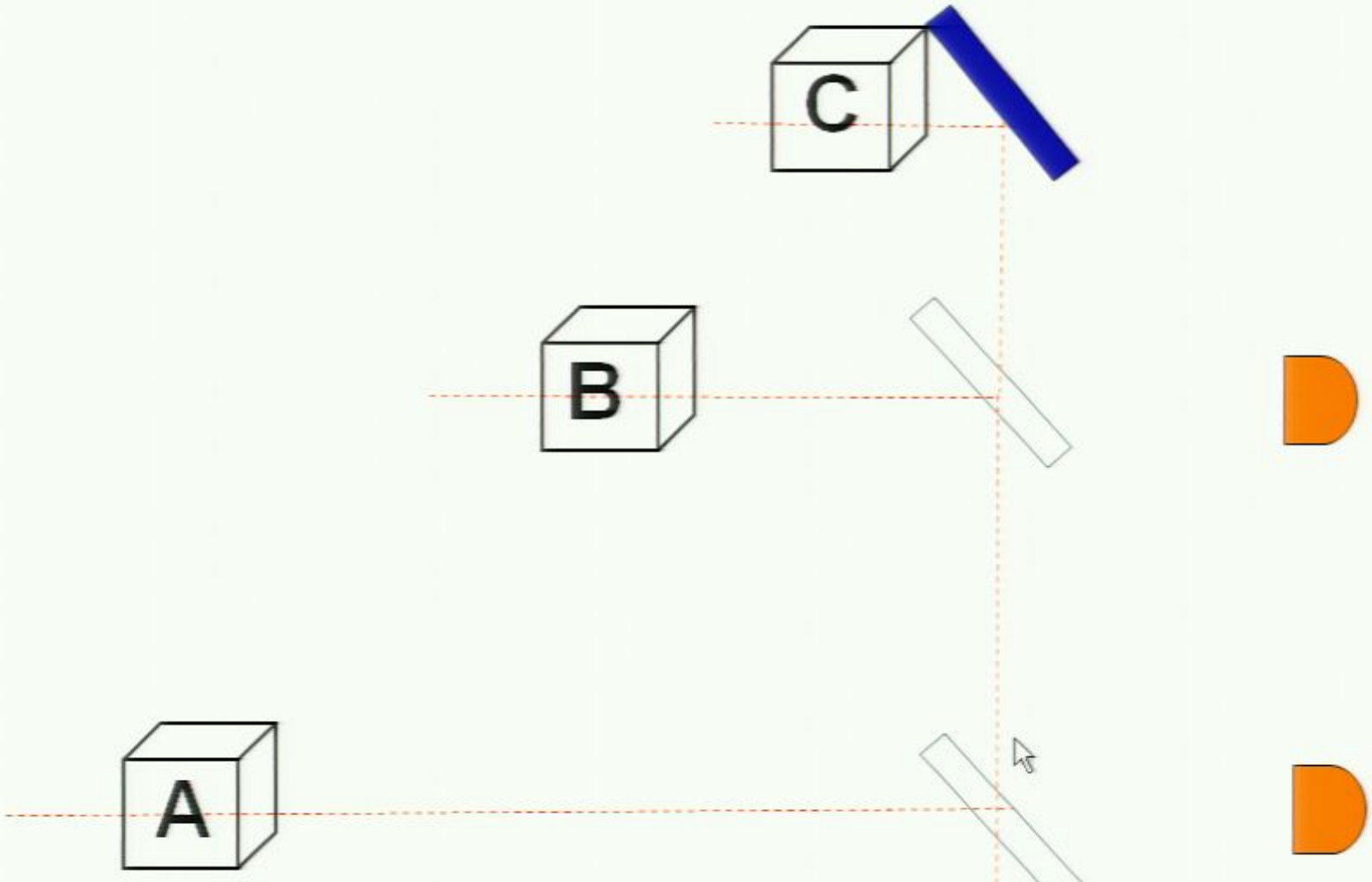

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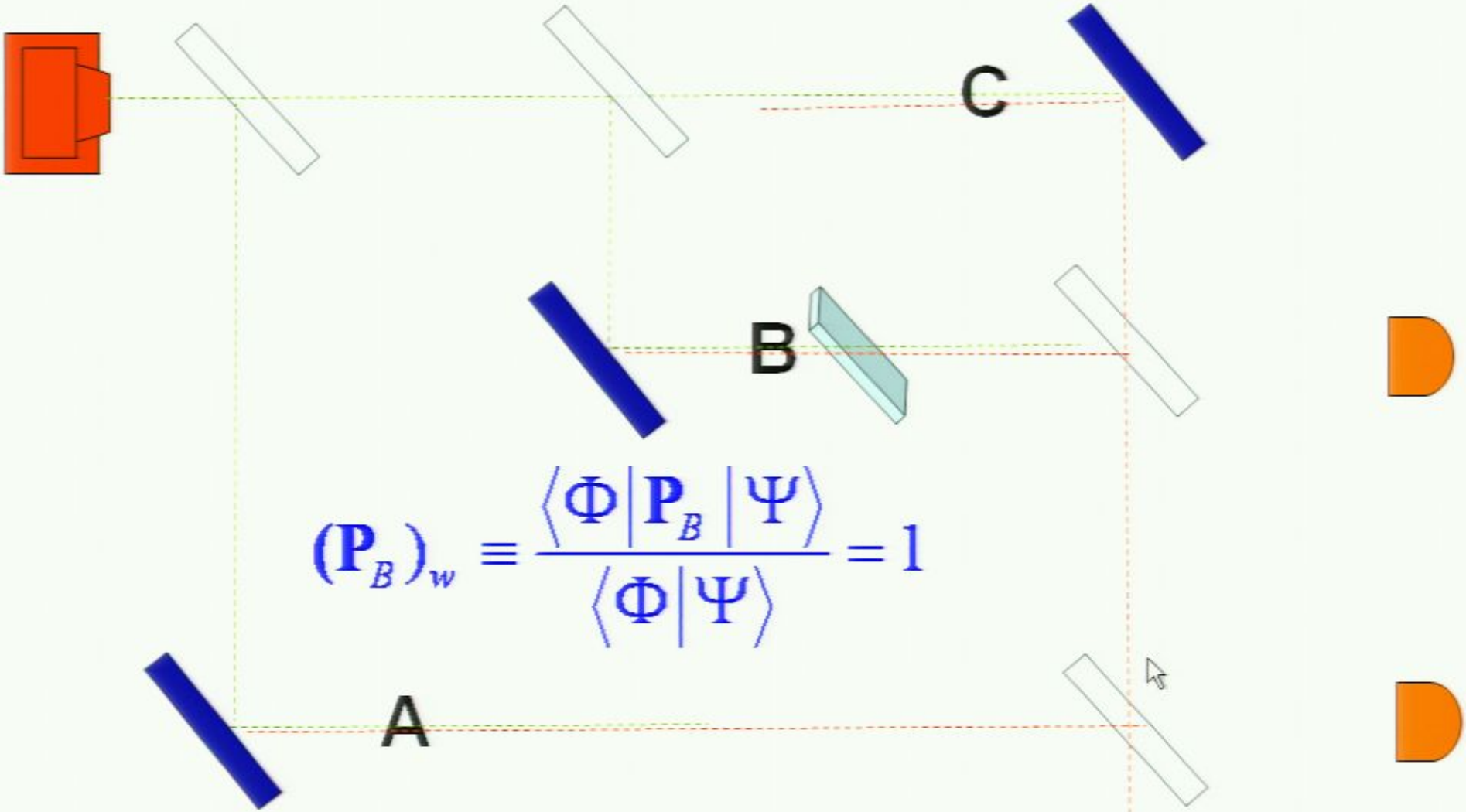

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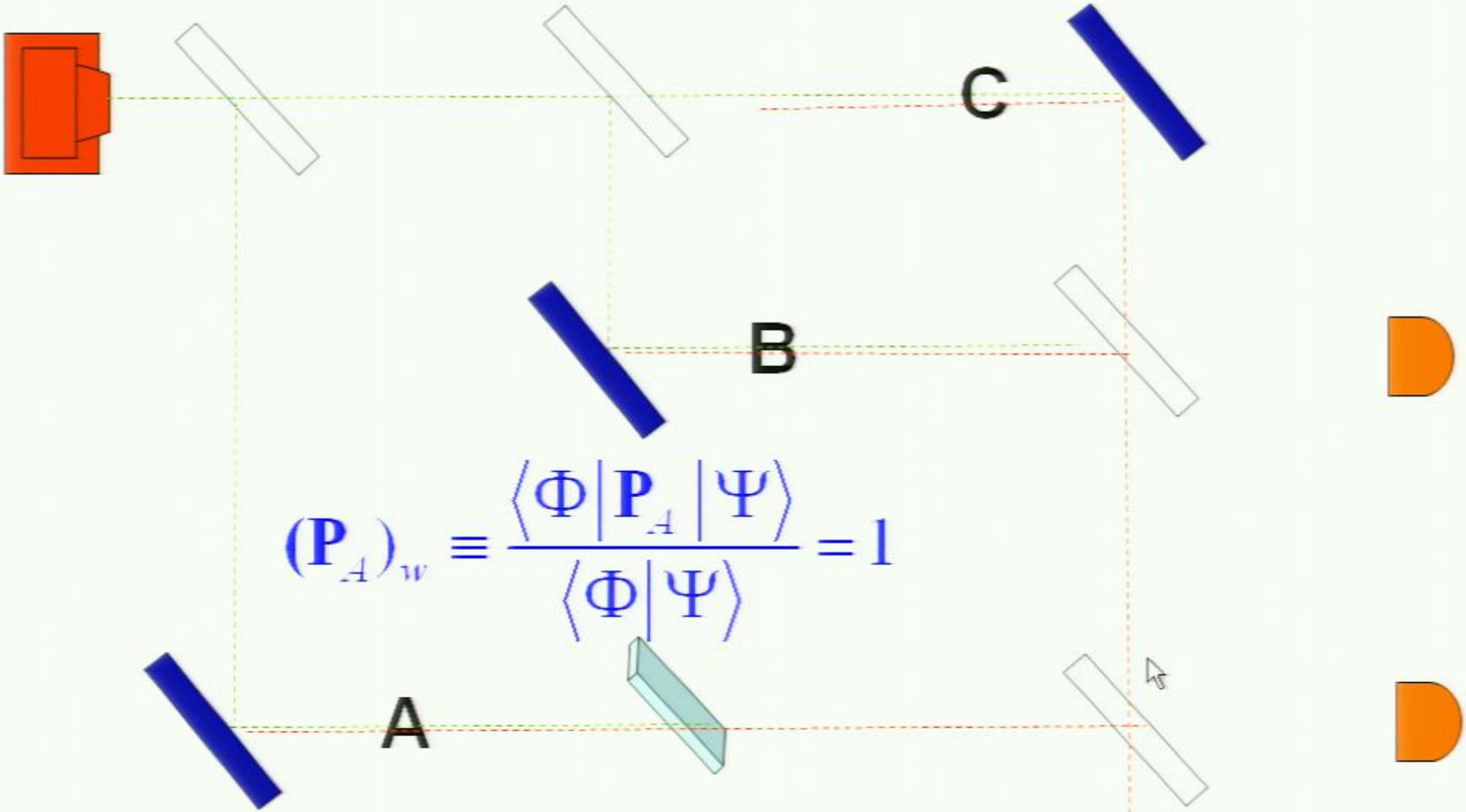

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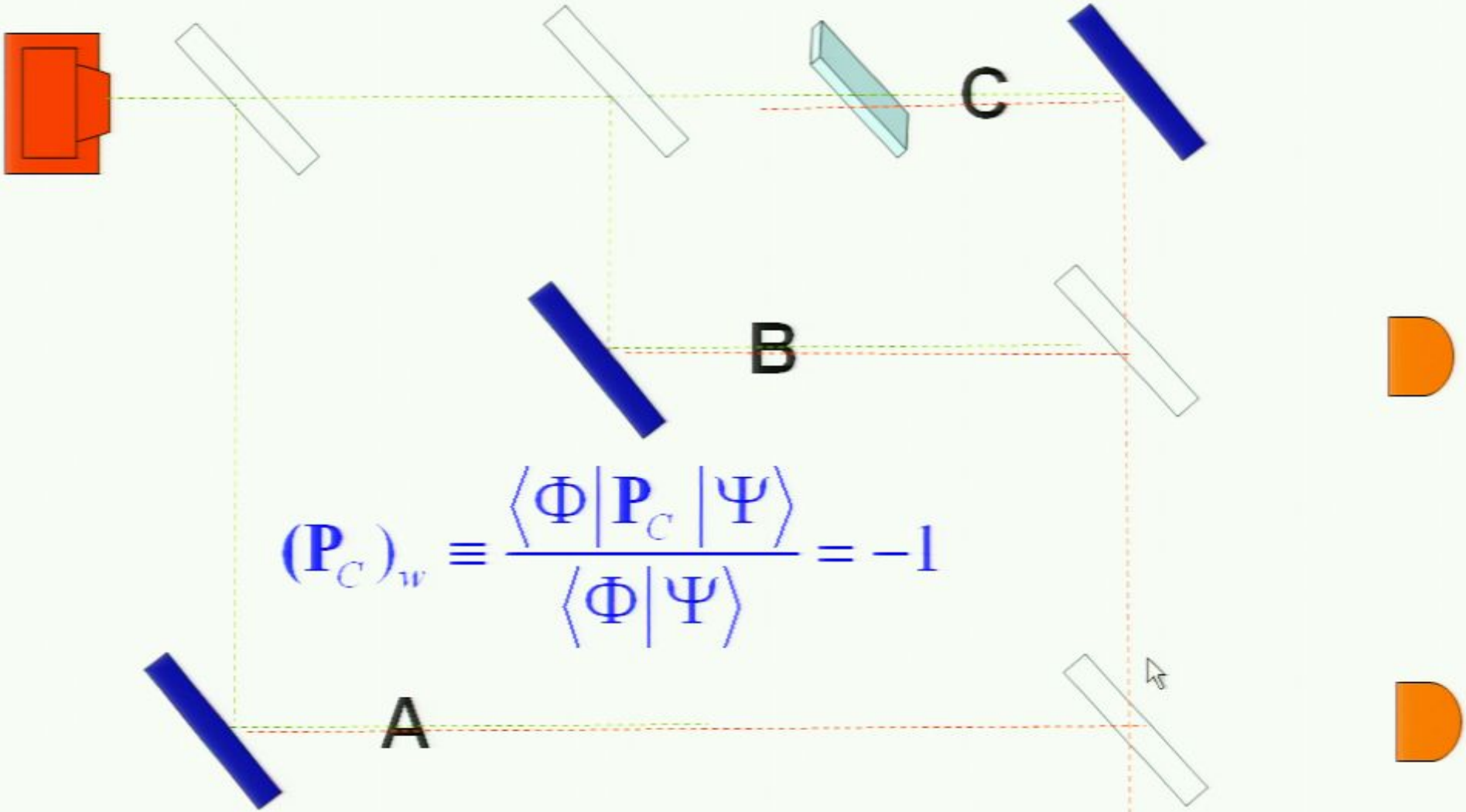

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(Resch *et al.*, Phys Lett A 324, 125(2004))

Weak measurement of C with post-selection

$$H_{\text{int}} = g(t) P_{MD} C$$

$$\langle P_{MD} \rangle = 0, \quad \Delta P_{MD} \text{ small}$$

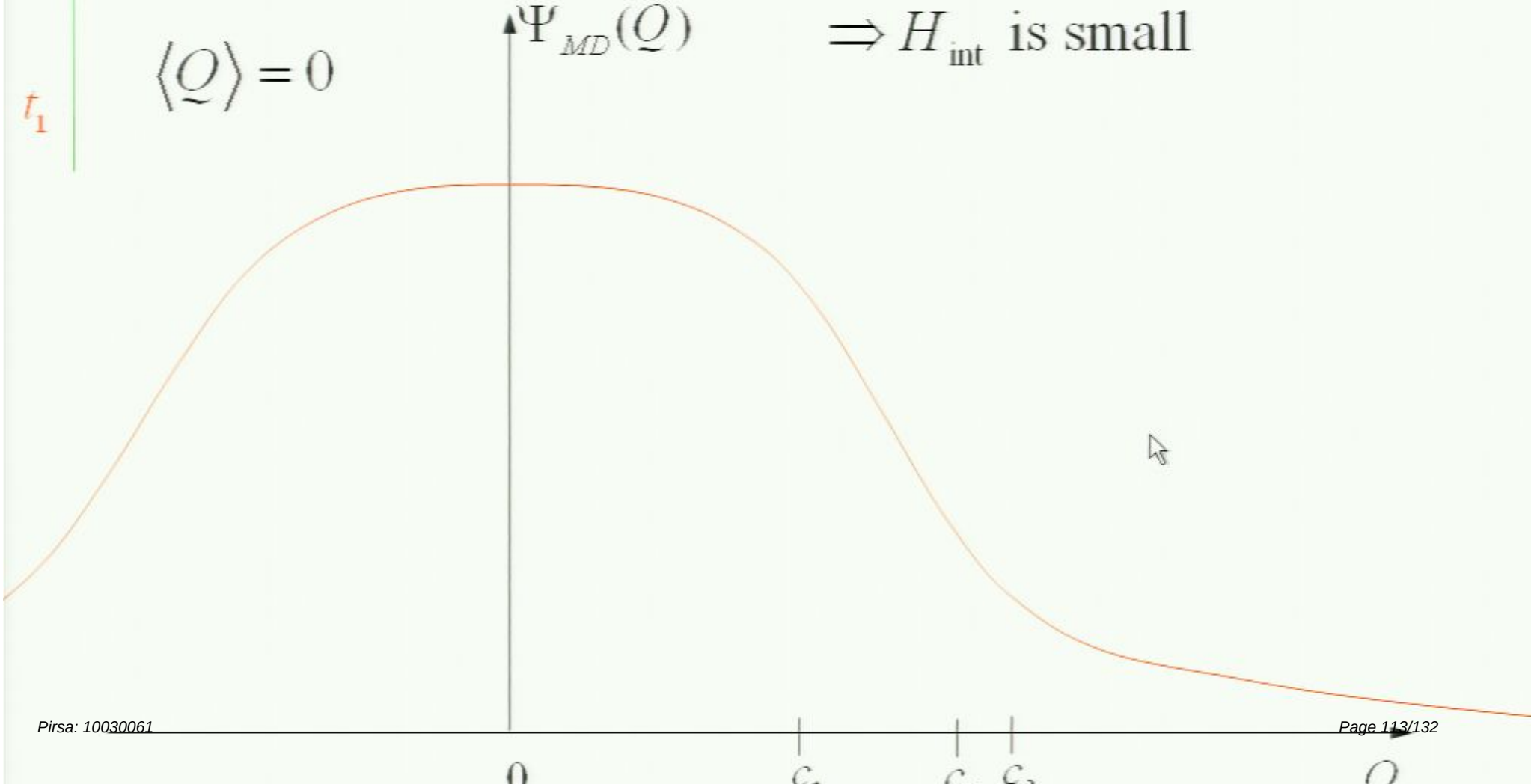
$$\Rightarrow H_{\text{int}} \text{ is small}$$

t_2

t

t_1

$\langle Q \rangle = 0$



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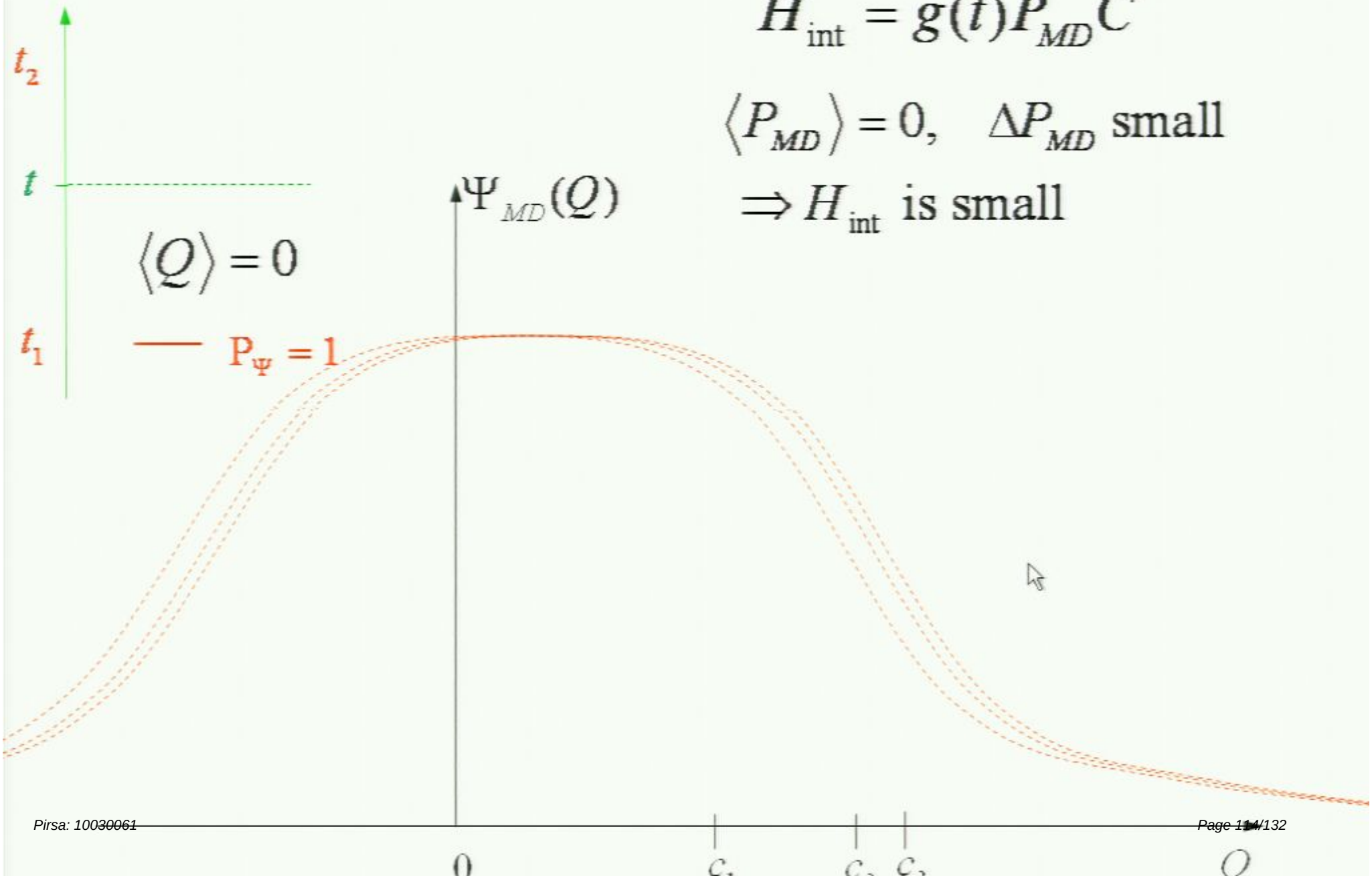

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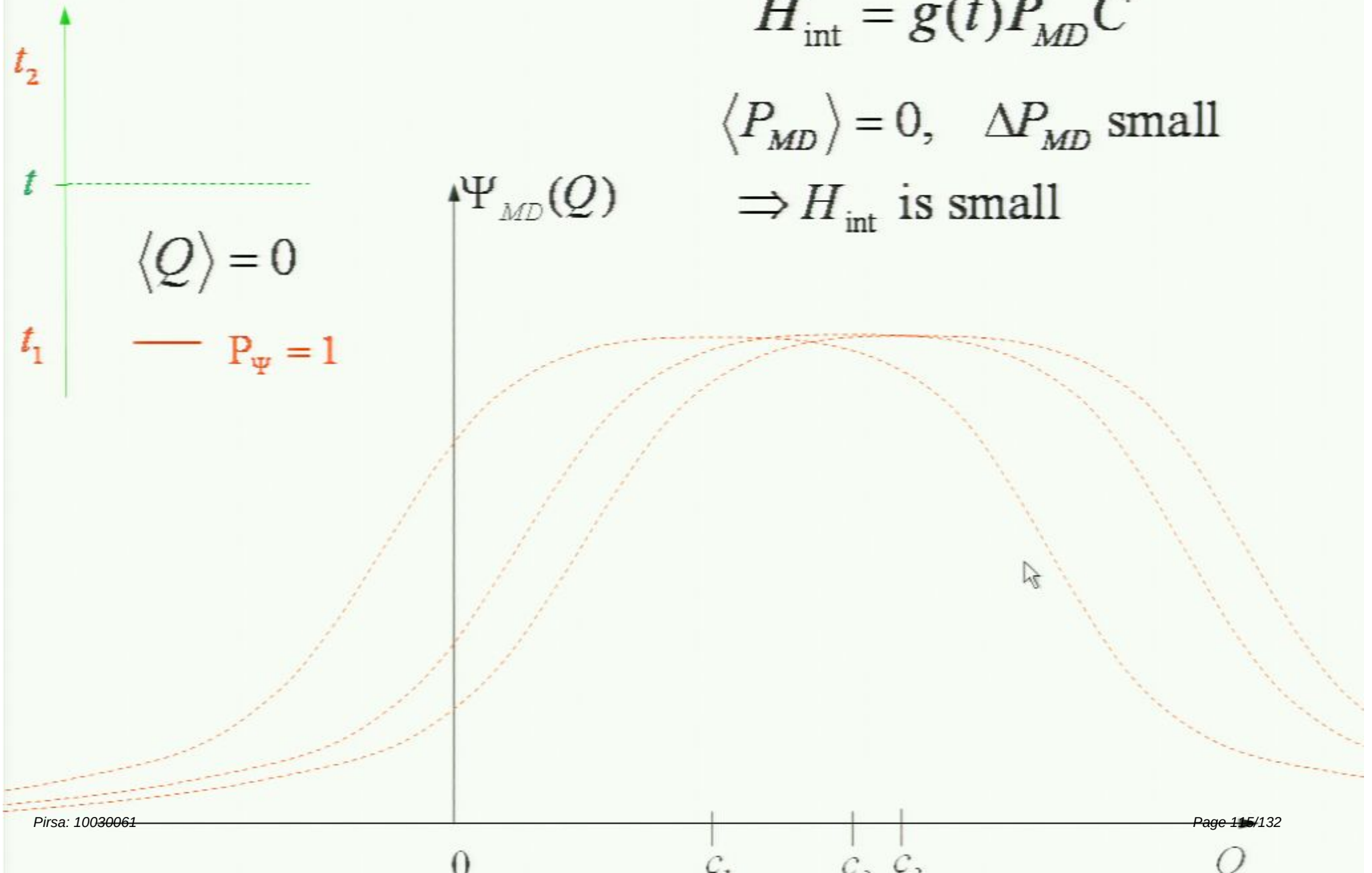

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t

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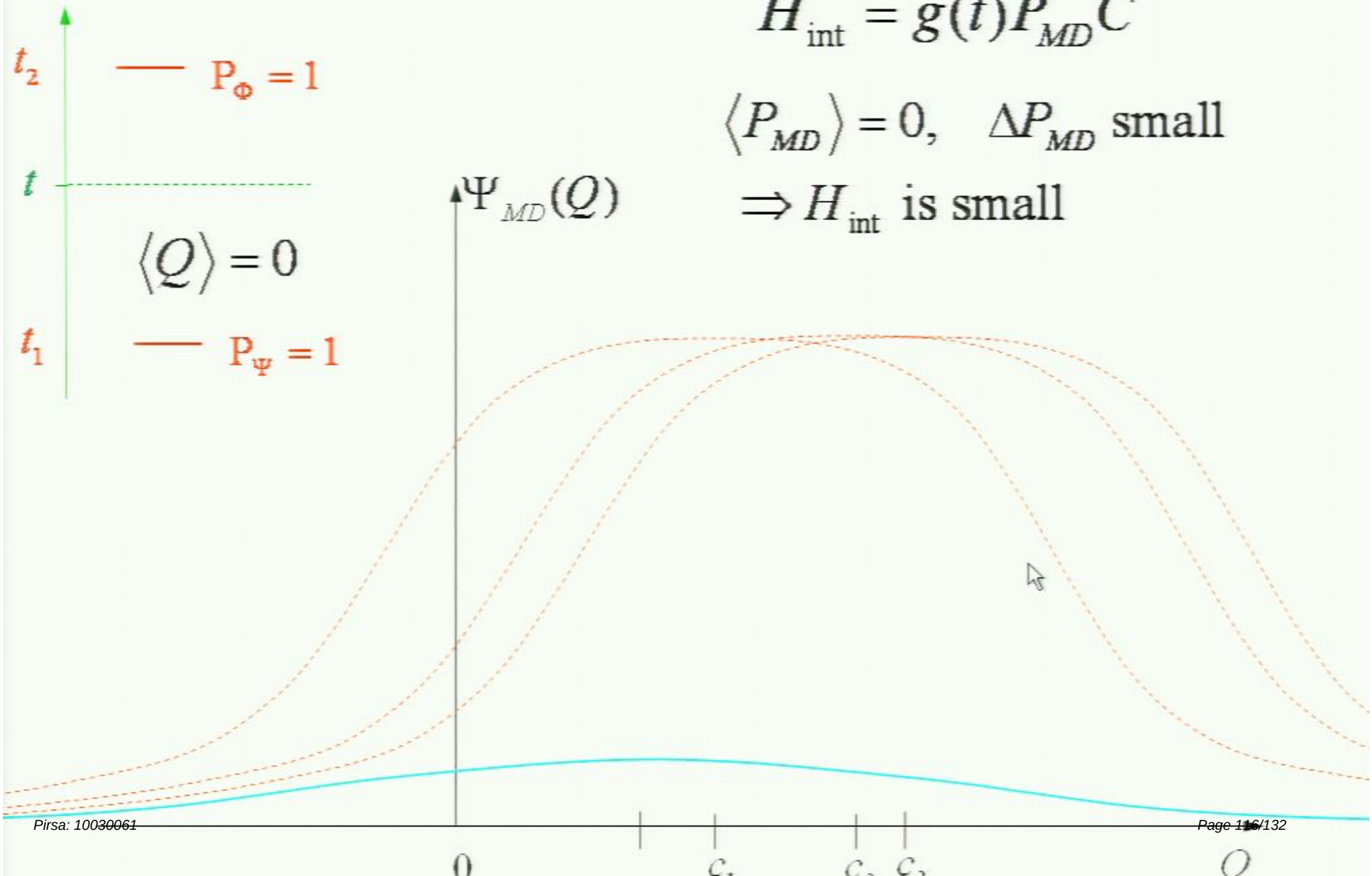
t_1 — $P_\Psi = 1$



Weak measurement of C with post-selection

$$\langle Q_{fin} \rangle = C_w$$

t_2 — $P_\Phi = 1$

t

$\langle Q \rangle = 0$

t_1 — $P_\Psi = 1$

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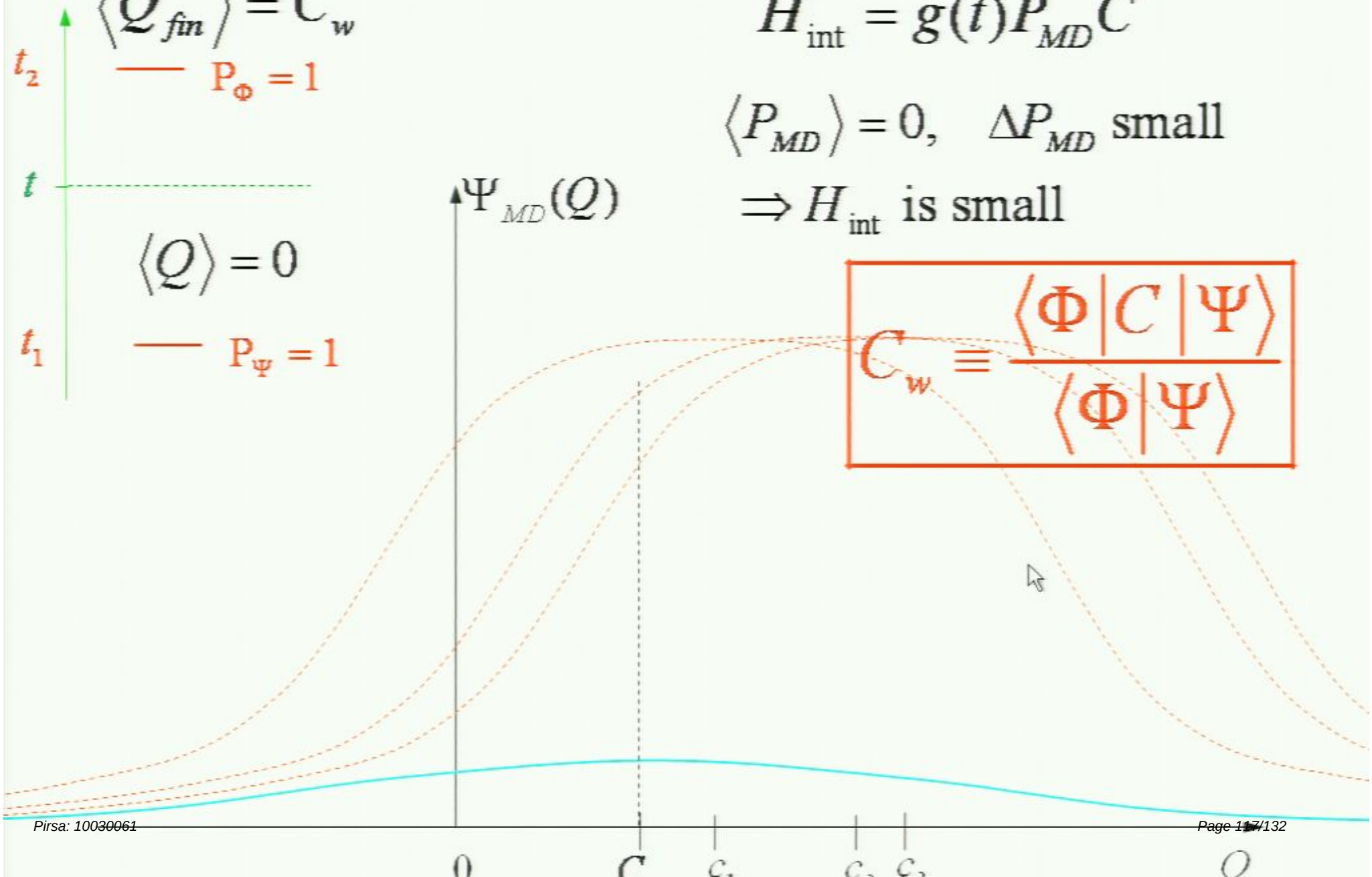

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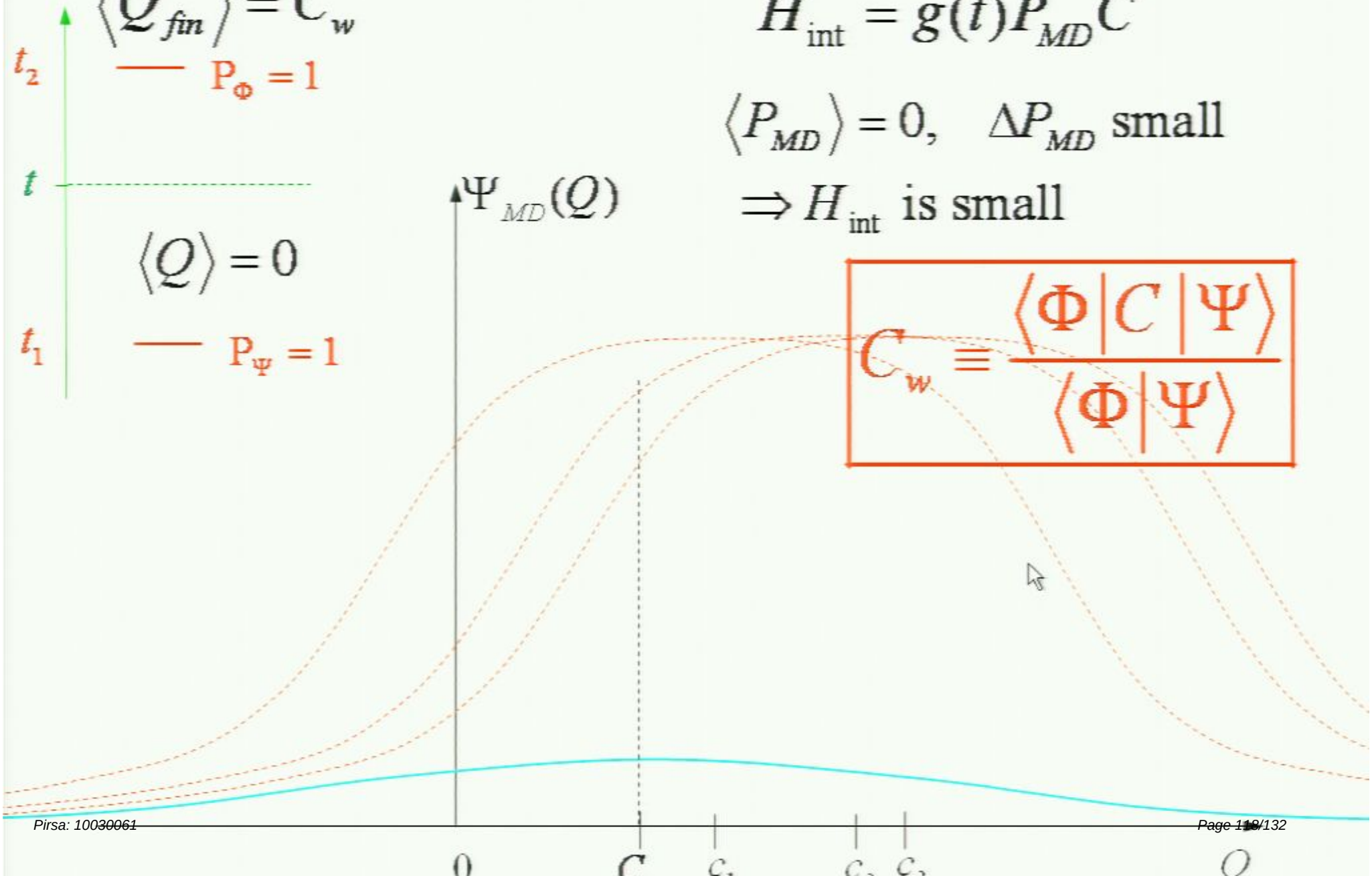
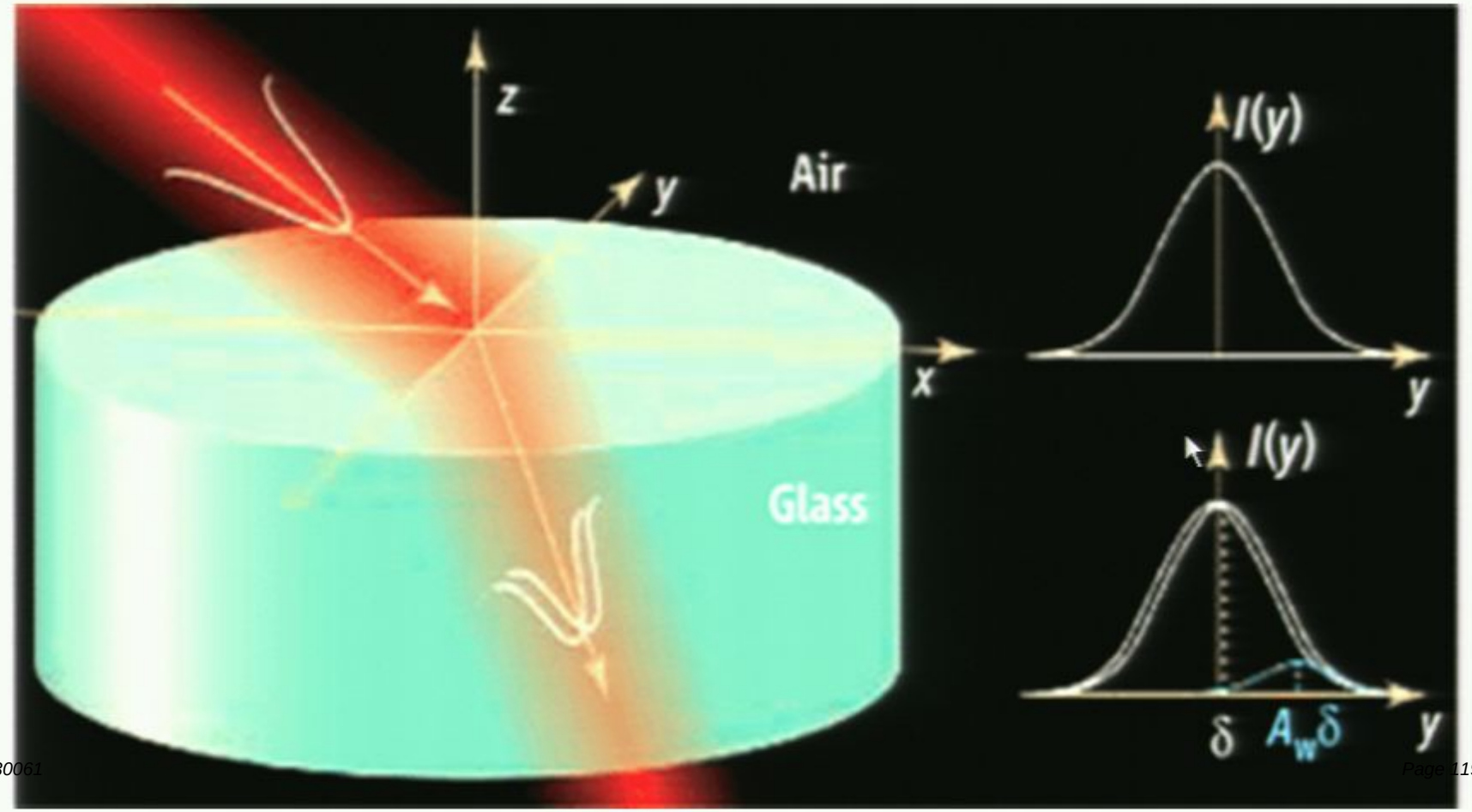


Science 2008: O. Hosten and P. Kwiat

Observation of the Spin Hall Effect of Light via Weak Measurements

"In the first work on weak measurement (AAV), it was speculated that the technique could be useful in amplifying and measuring small effects. Now, 20 years later, this potential has finally been realized."



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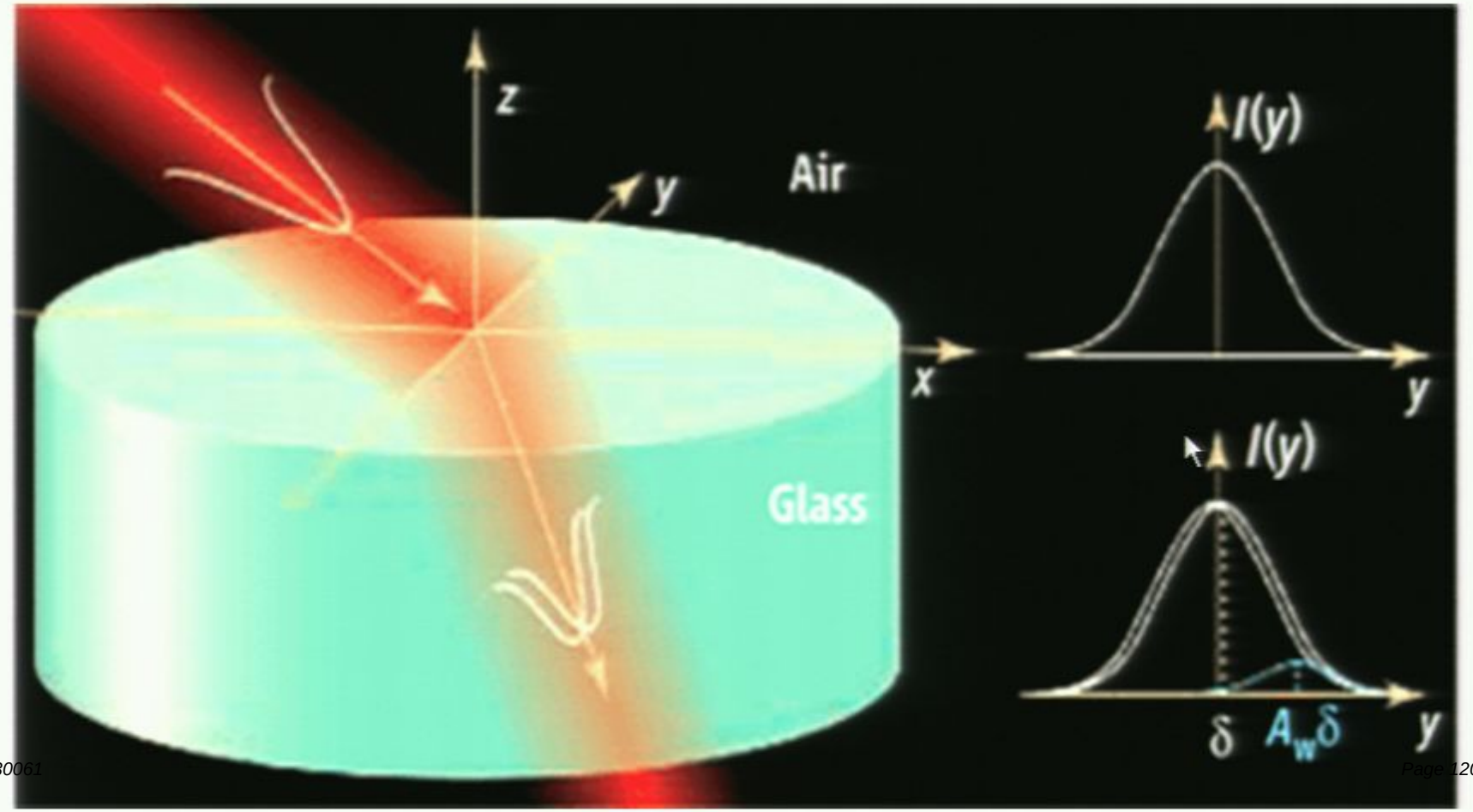
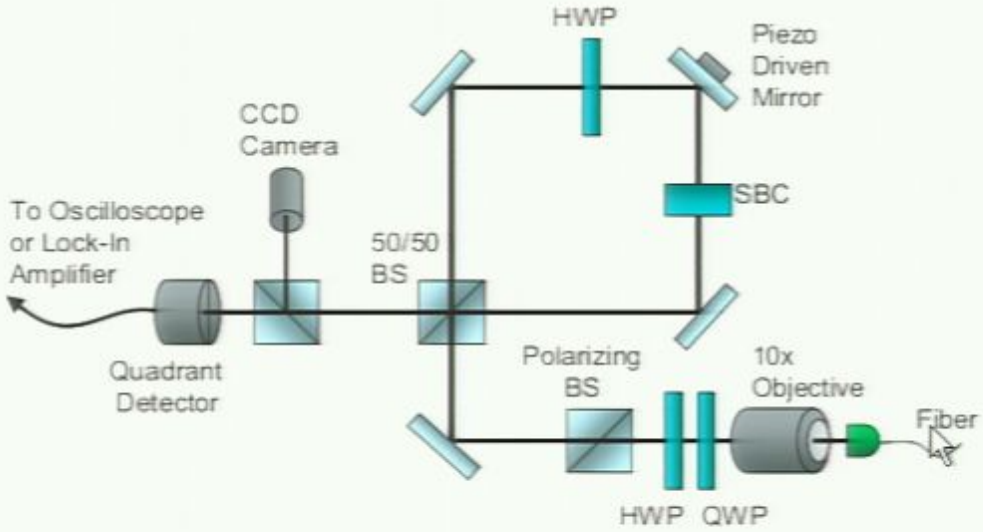


Ultrasensitive Beam Deflection Measurement via Interferometric Weak Value Amplification

P. Ben Dixon, David J. Starling, Andrew N. Jordan, and John C. Howell



By tuning the interferometer and monitoring the resulting small amount of light exiting the interferometer dark port, weak value amplification factors of over 100 are achieved.

Weak measurement of C with post-selection

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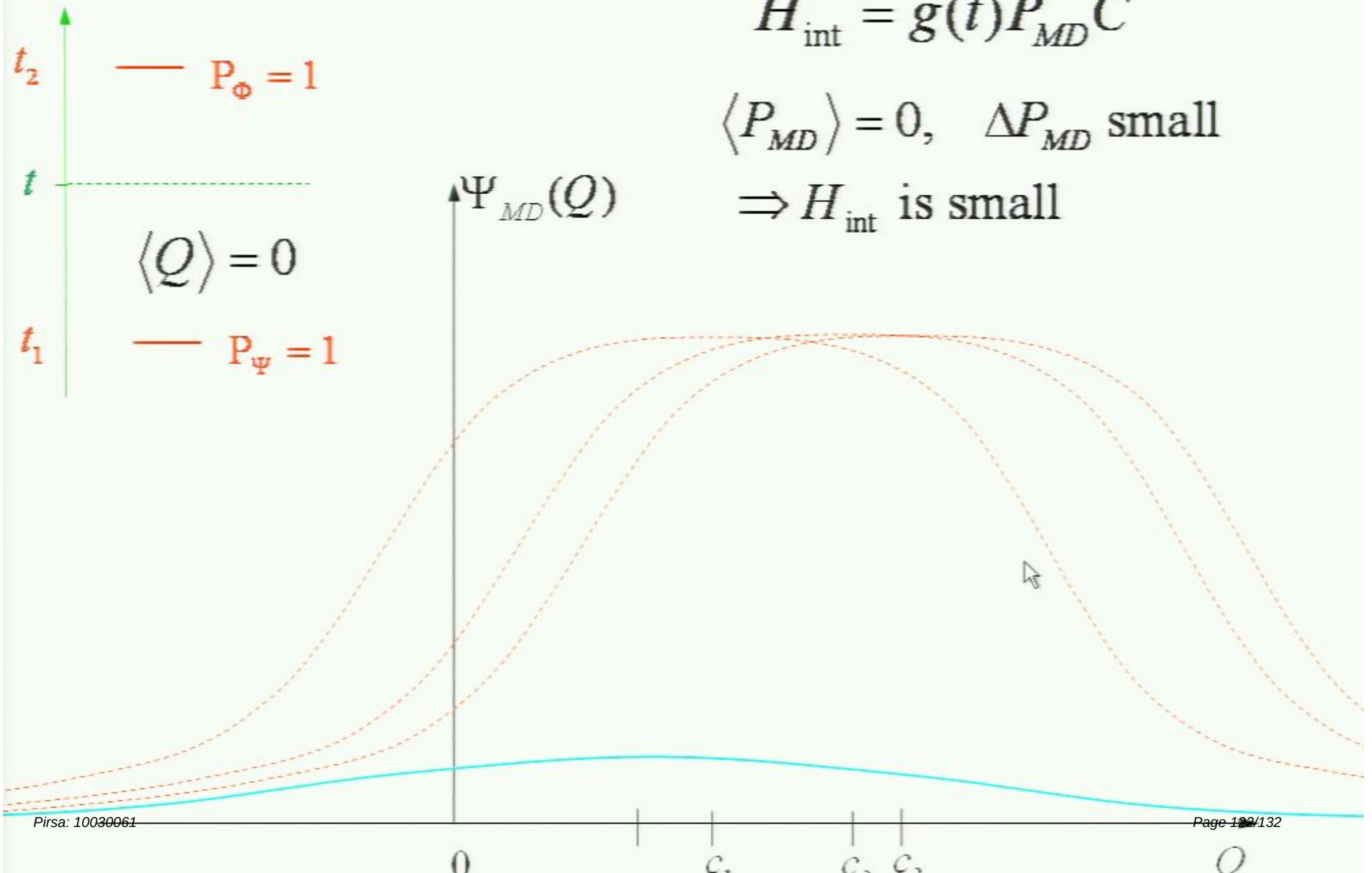
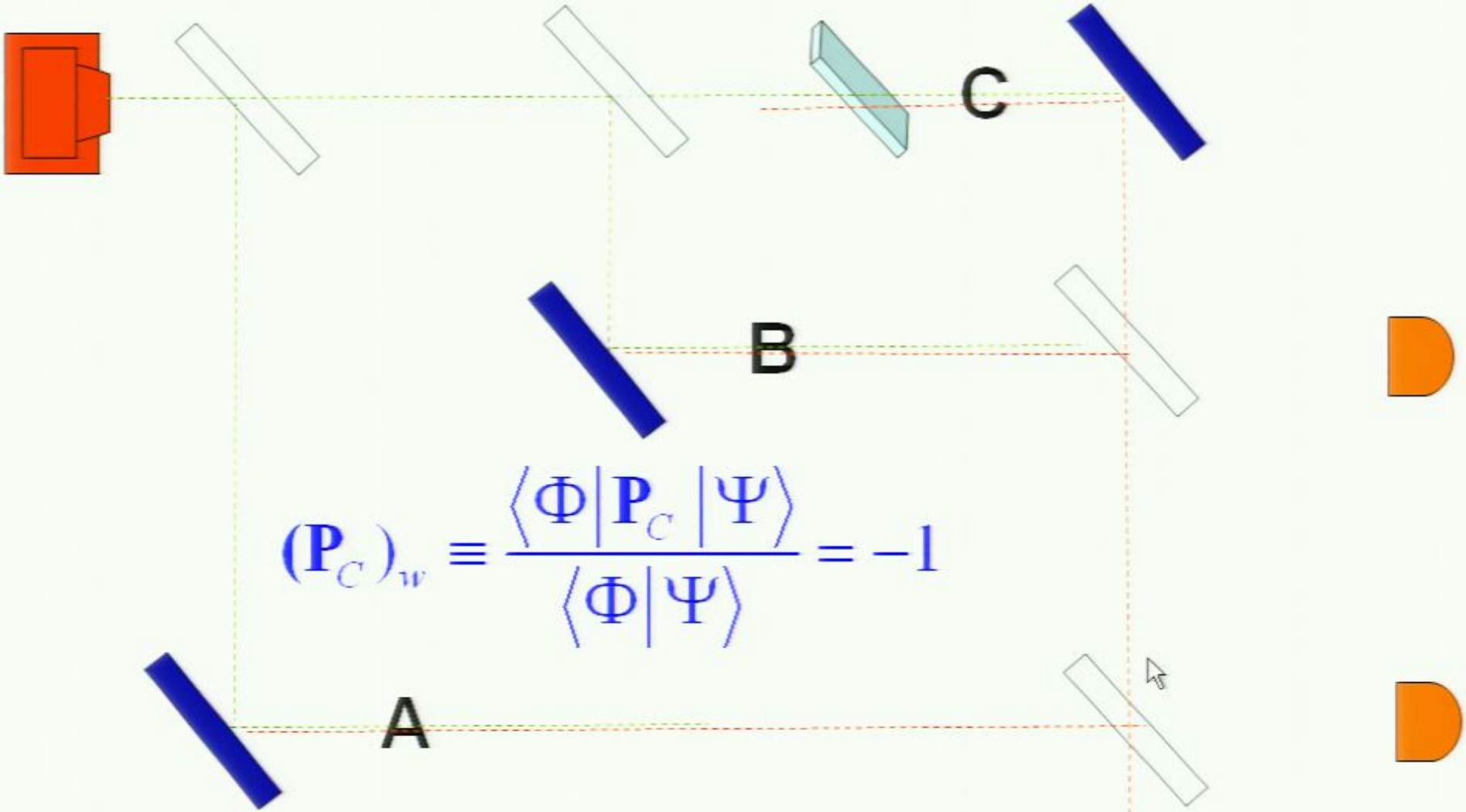


The two-state vector formalism explanation



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(Resch *et al.*, Phys Lett A 324, 125(2004))

Conclusions

It helps to ask: “Where is the particle between measurements?” and it helps to think about pre-and post-selected particles in terms of forward and backward evolving quantum states.

Wheeler's naive approach, according to which we decide about the past of a quantum particle based on the fact that ``it could not come the other way", has to be abandoned.

Only the two-state vector description of the quantum particle correctly describes the weak trace it leaves in its past.

Weak measurements have practical applications. Please, look for more.

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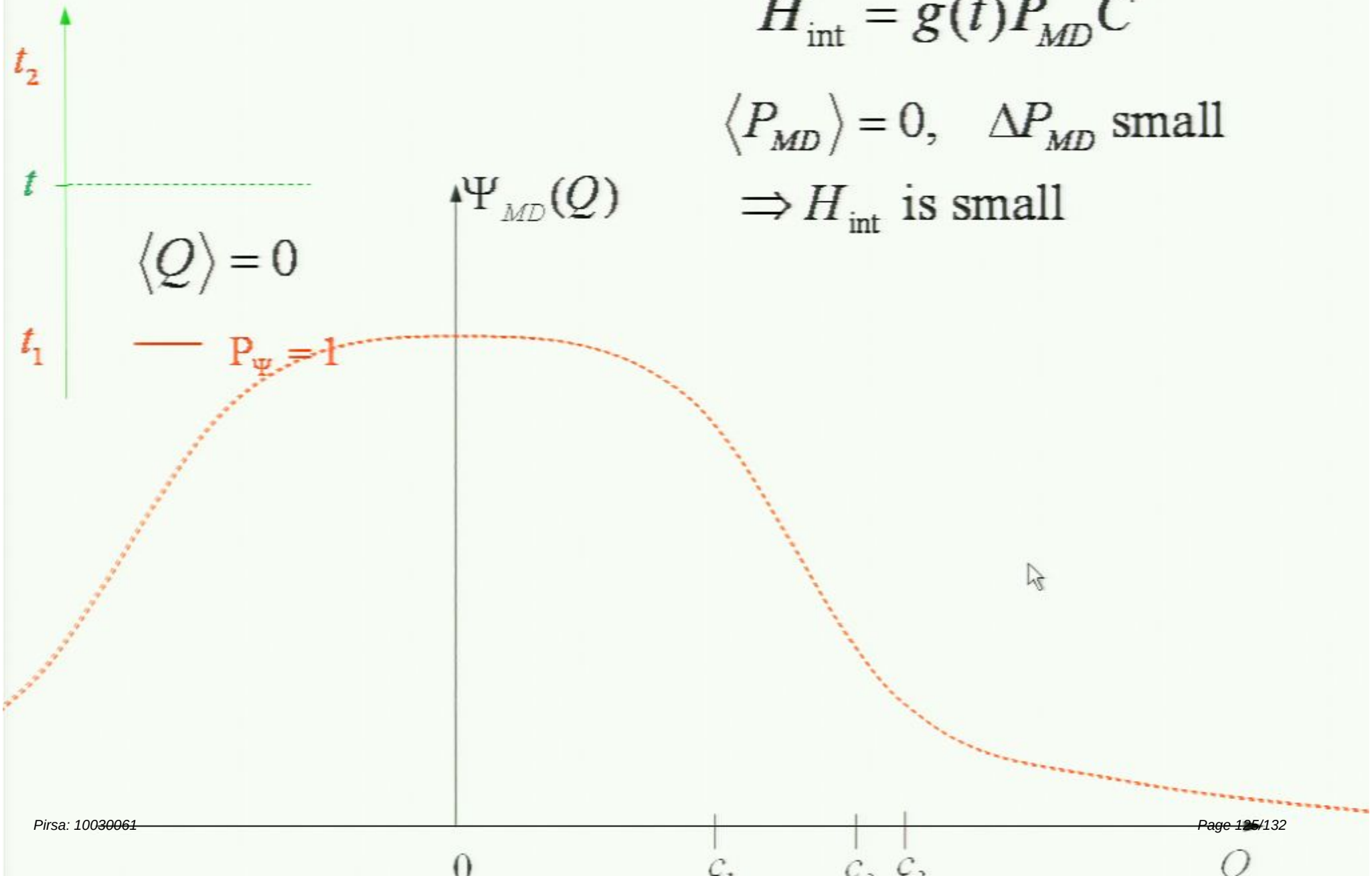

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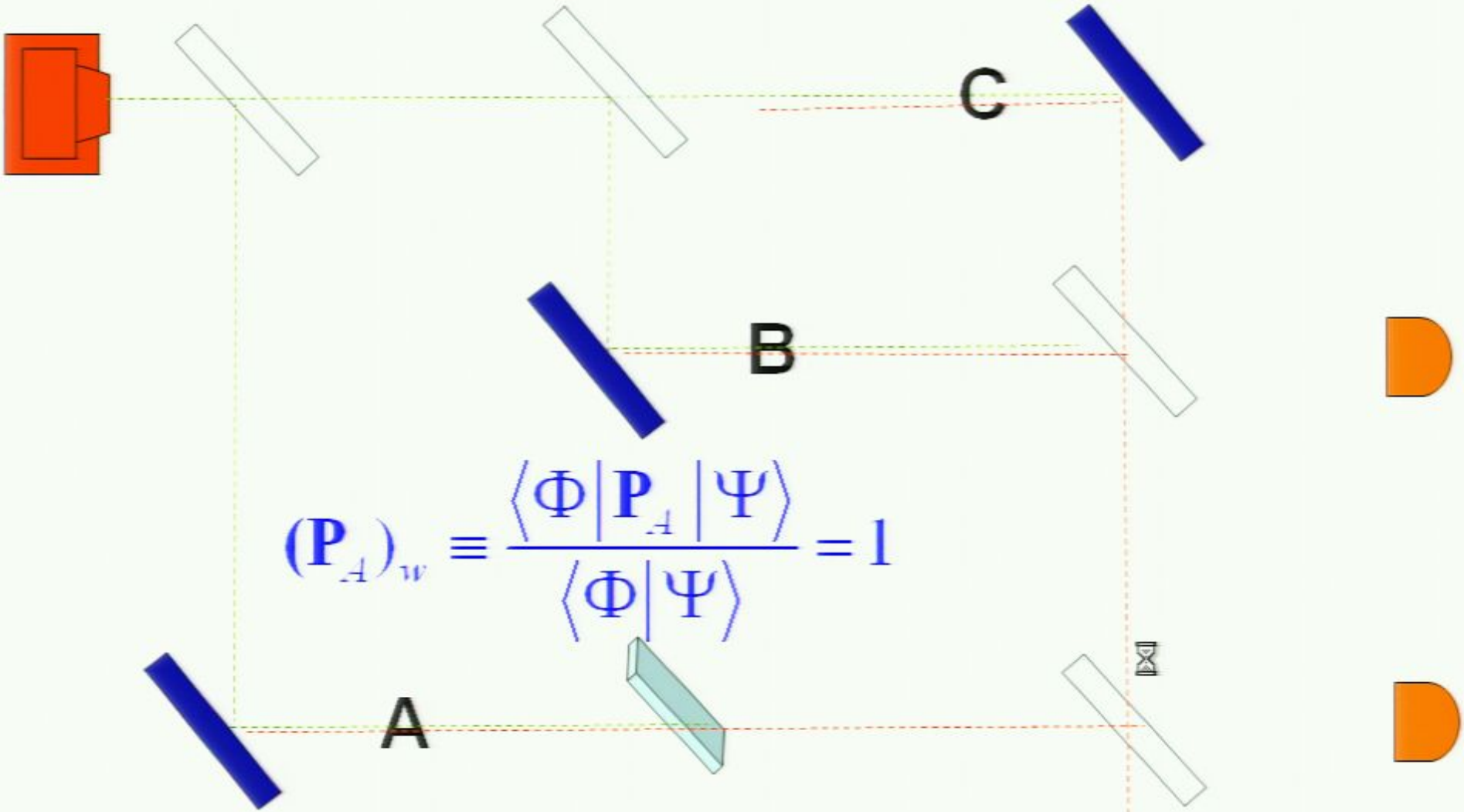

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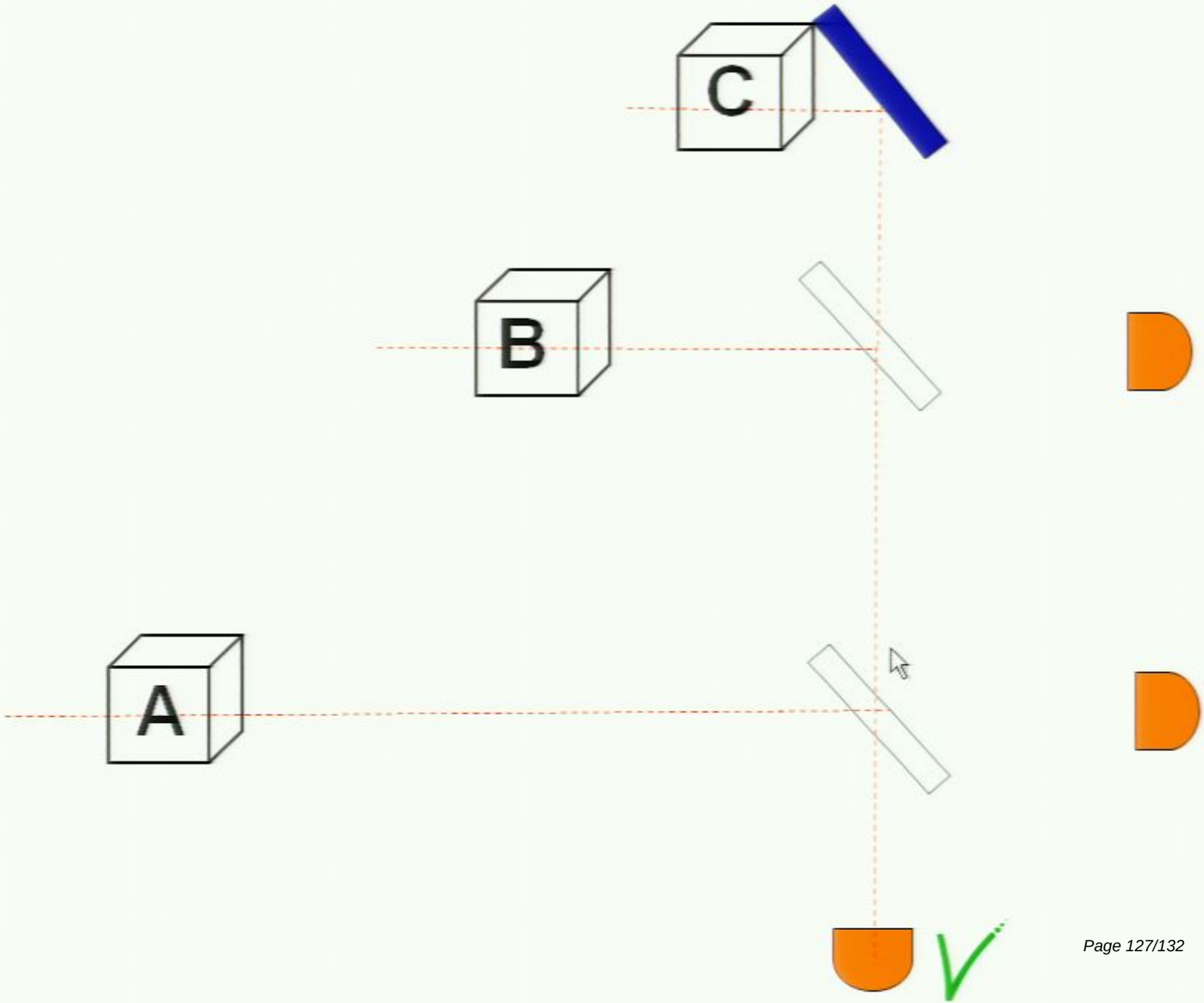

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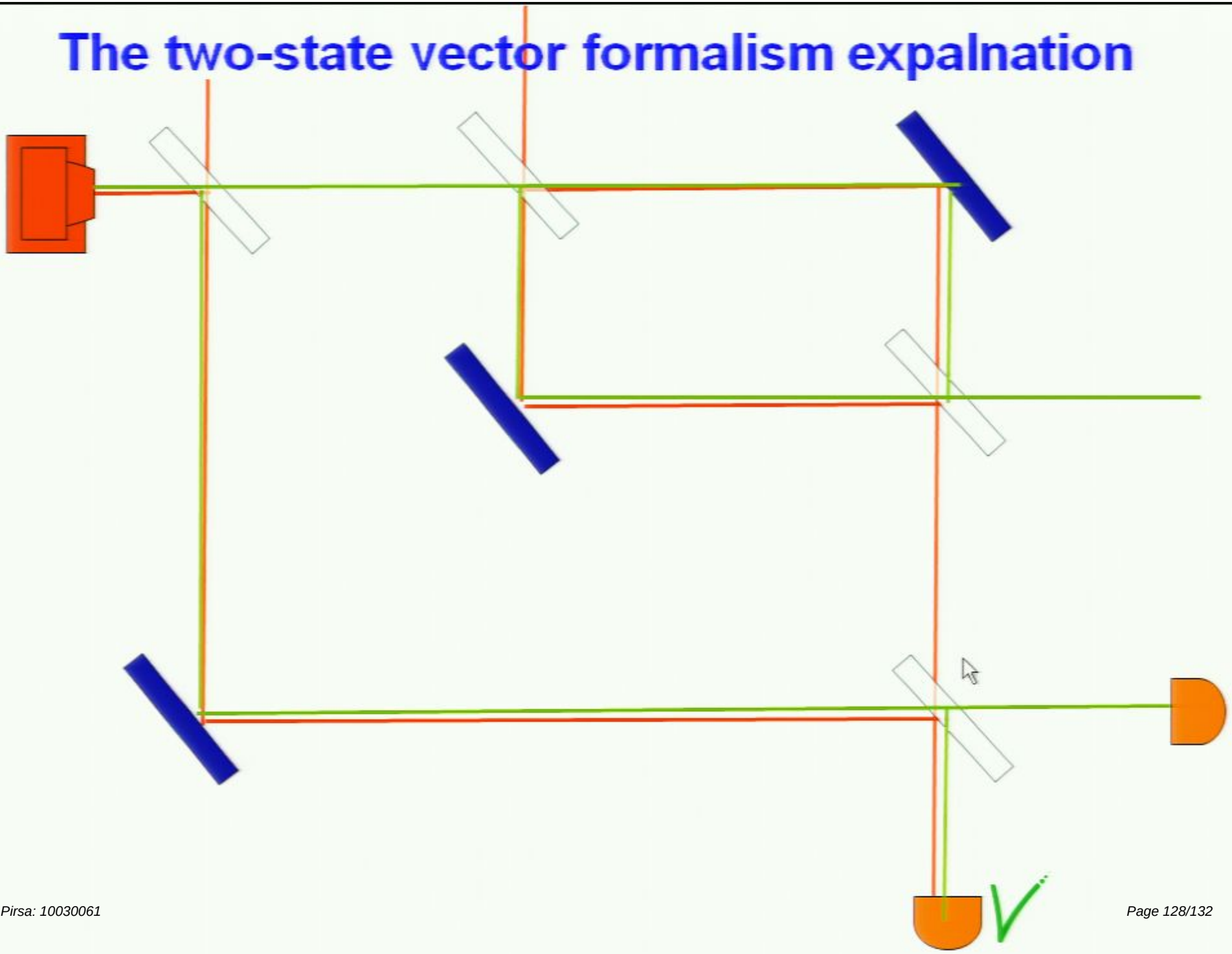

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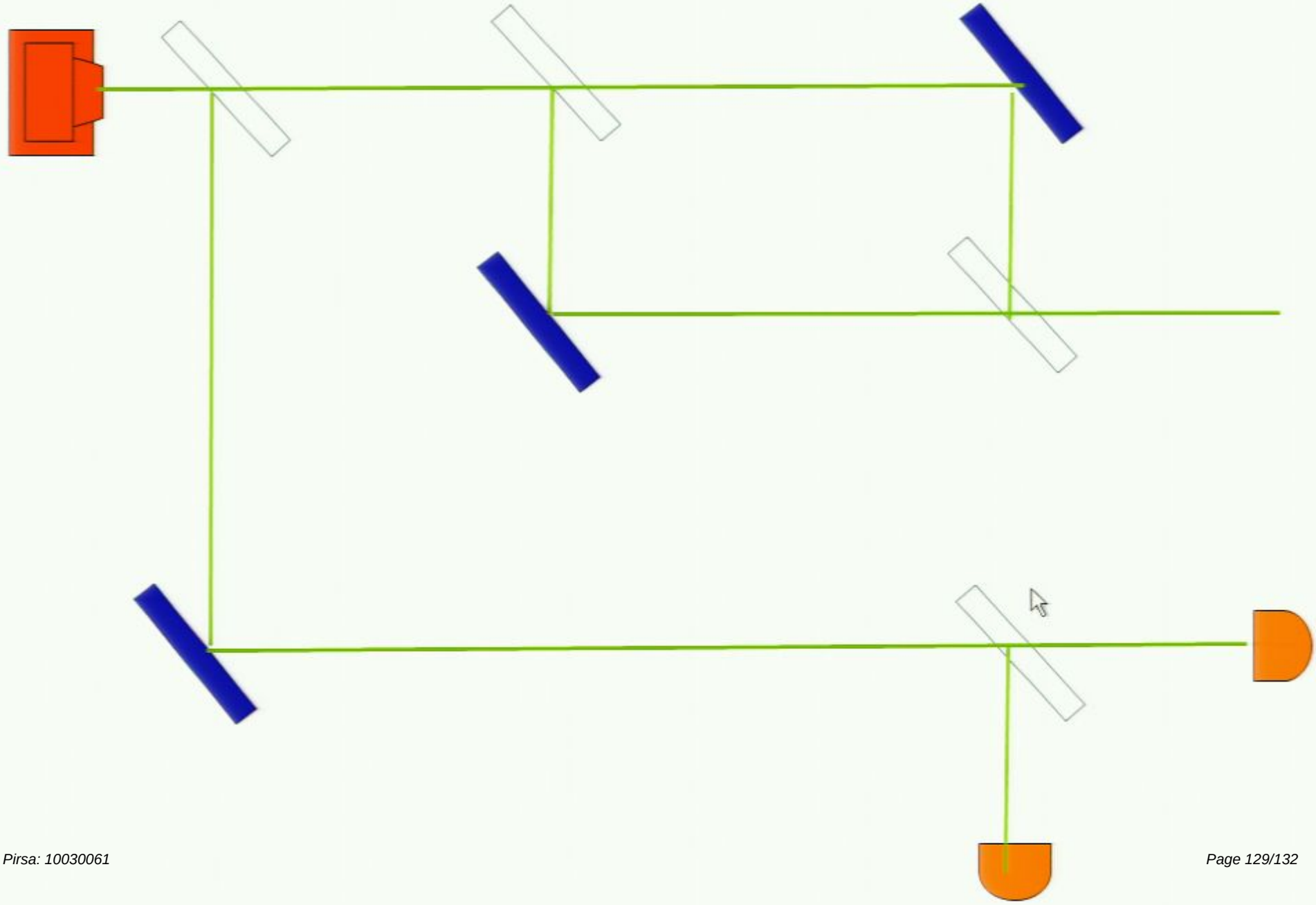

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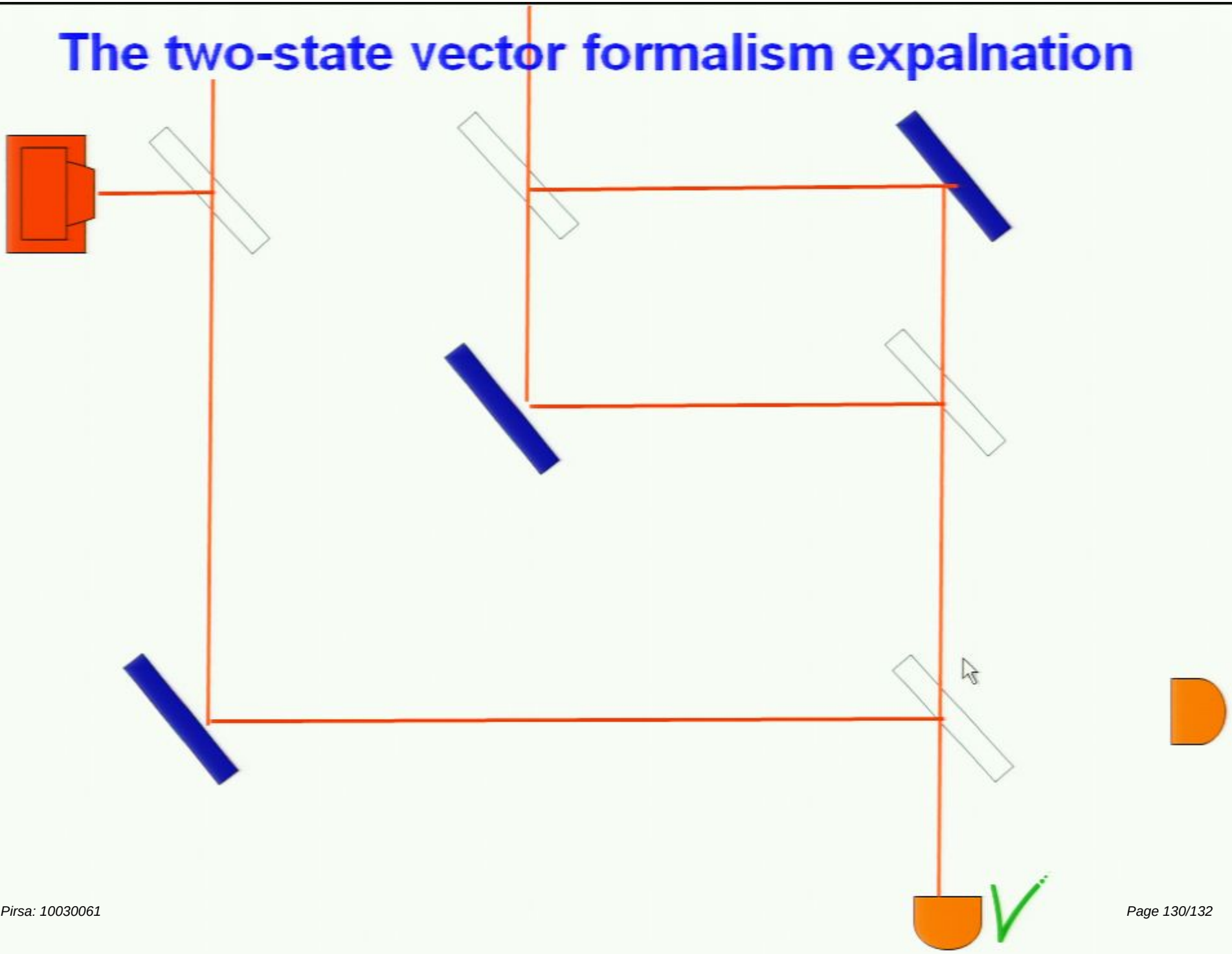

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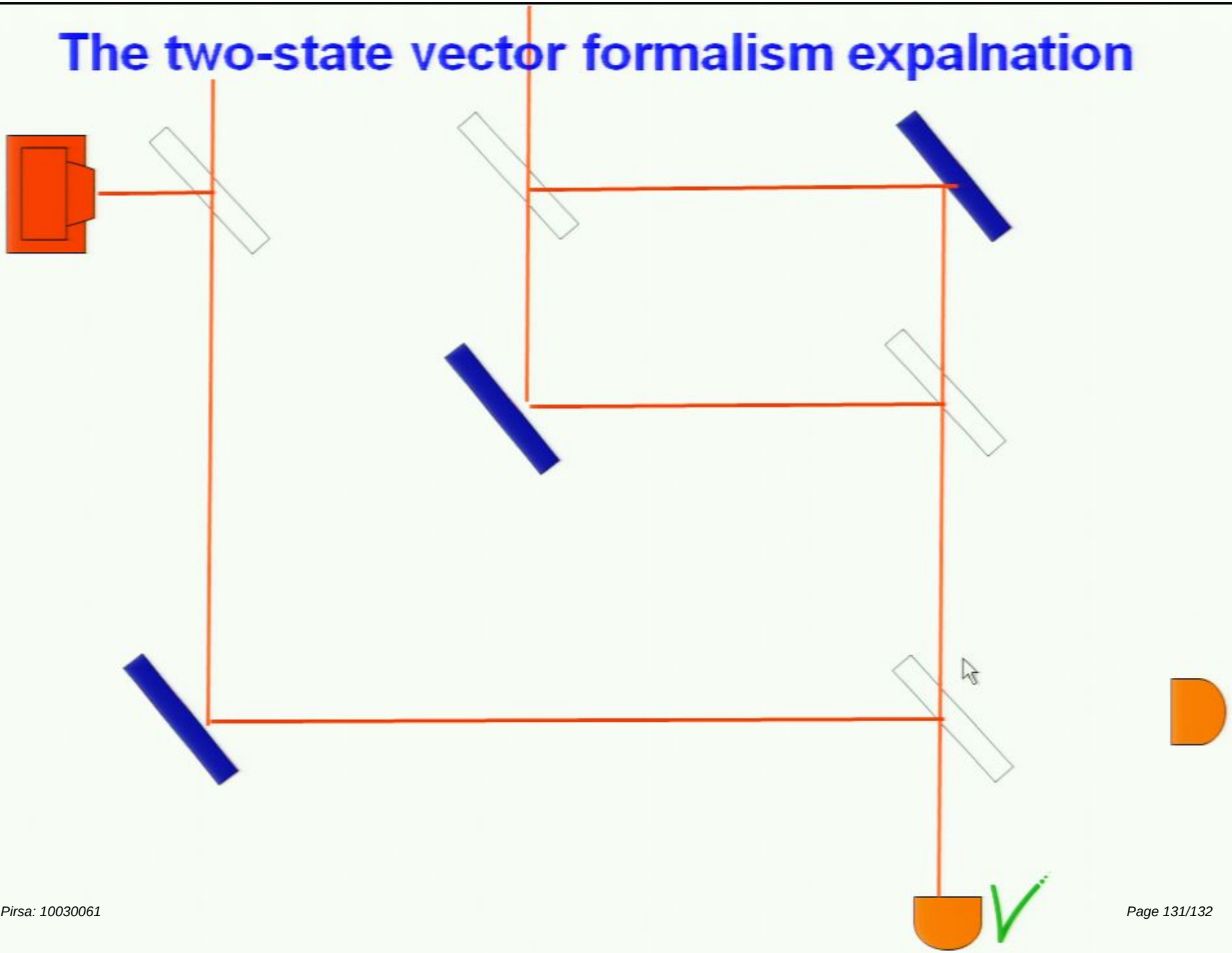

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