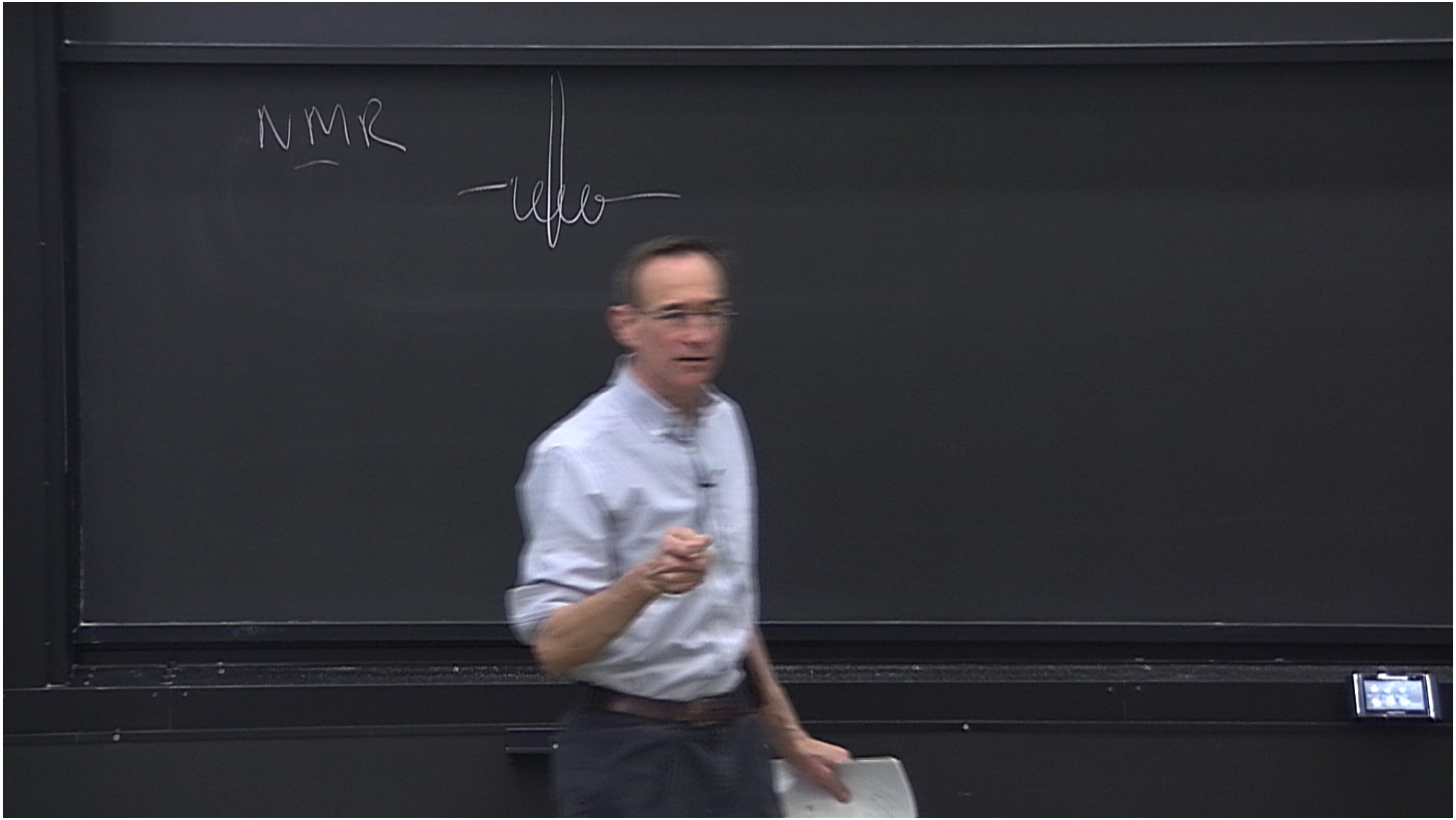
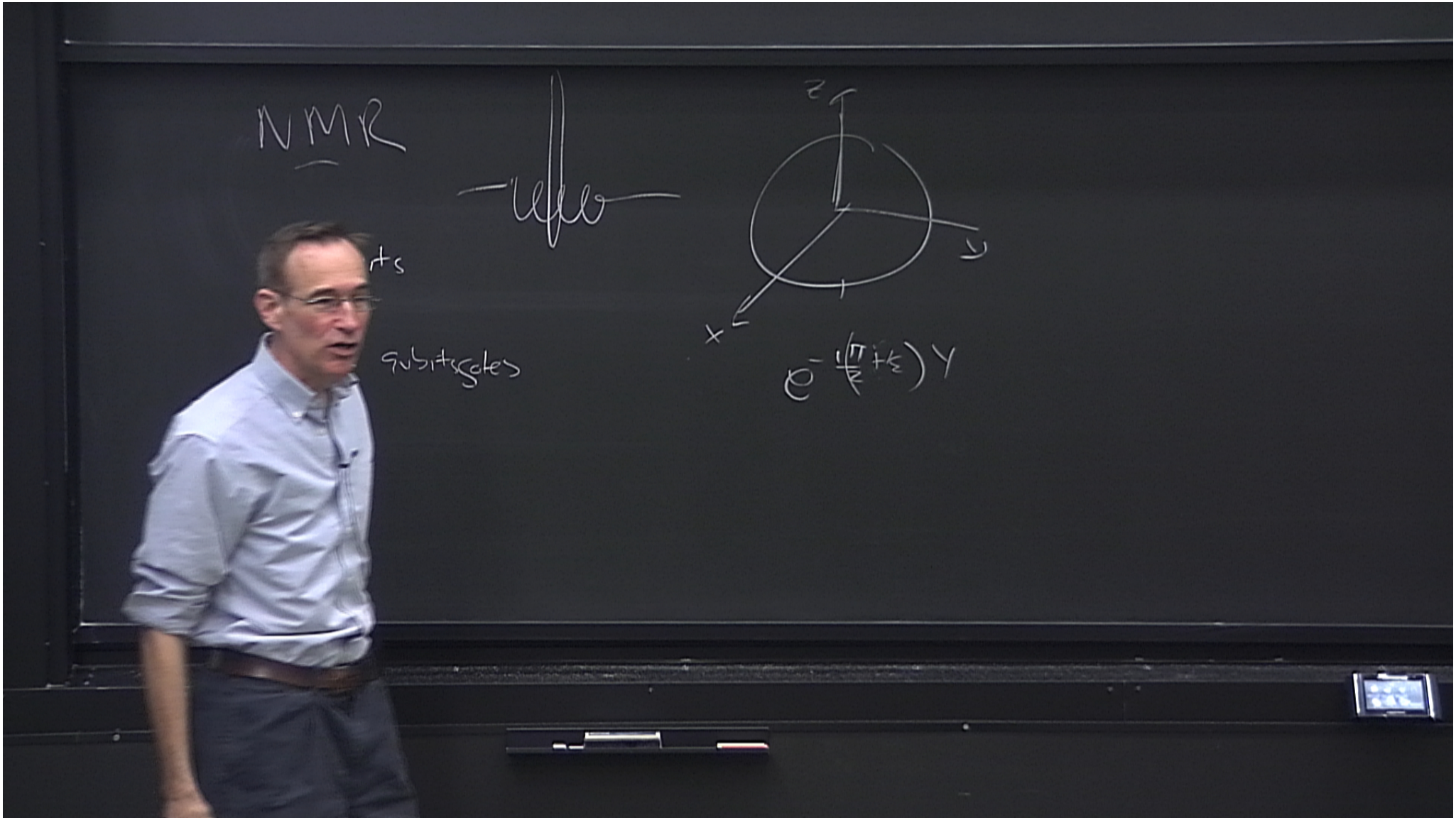
Title: PSI 2015/2016 Quantum Information - Lecture 7

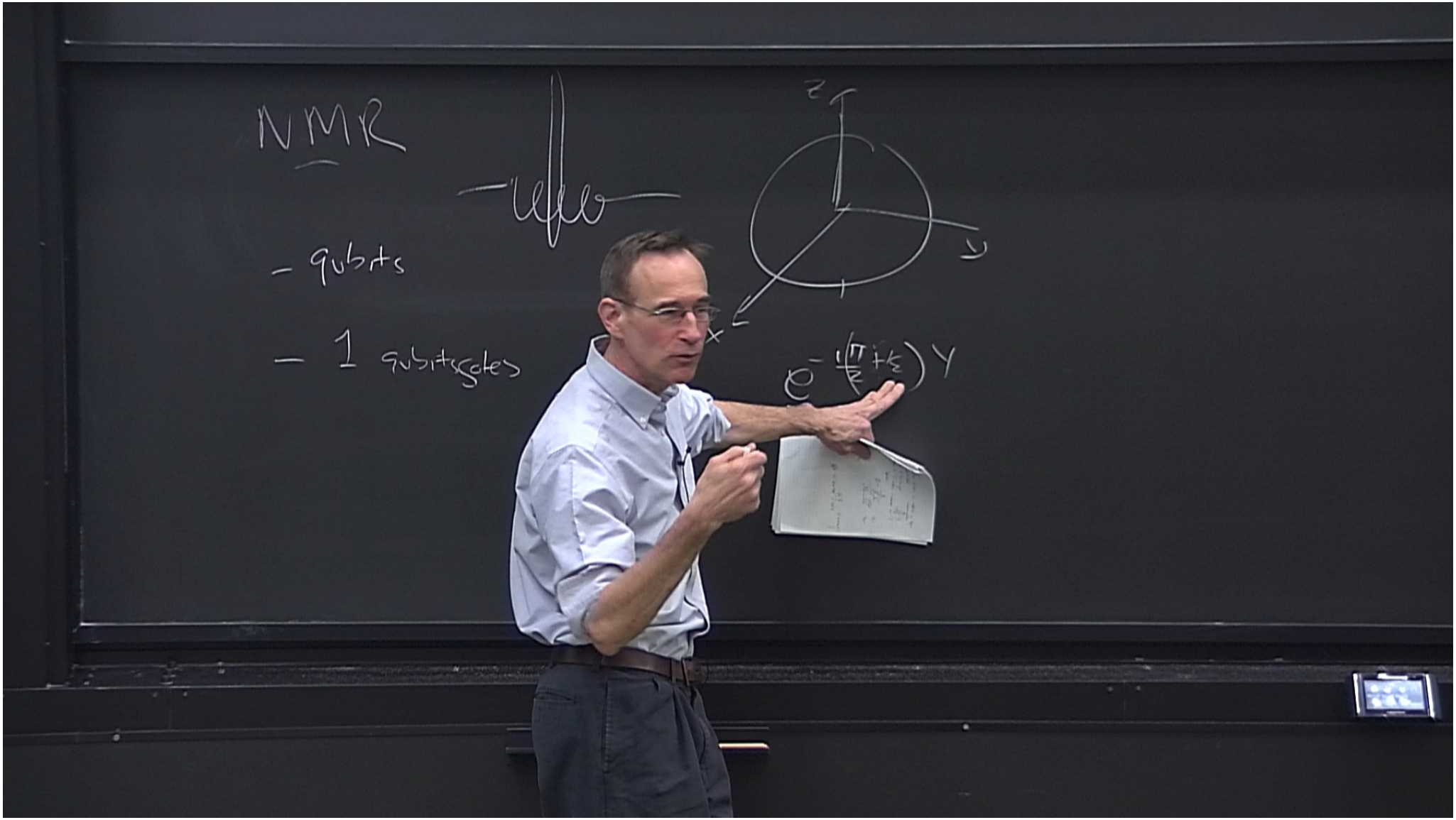
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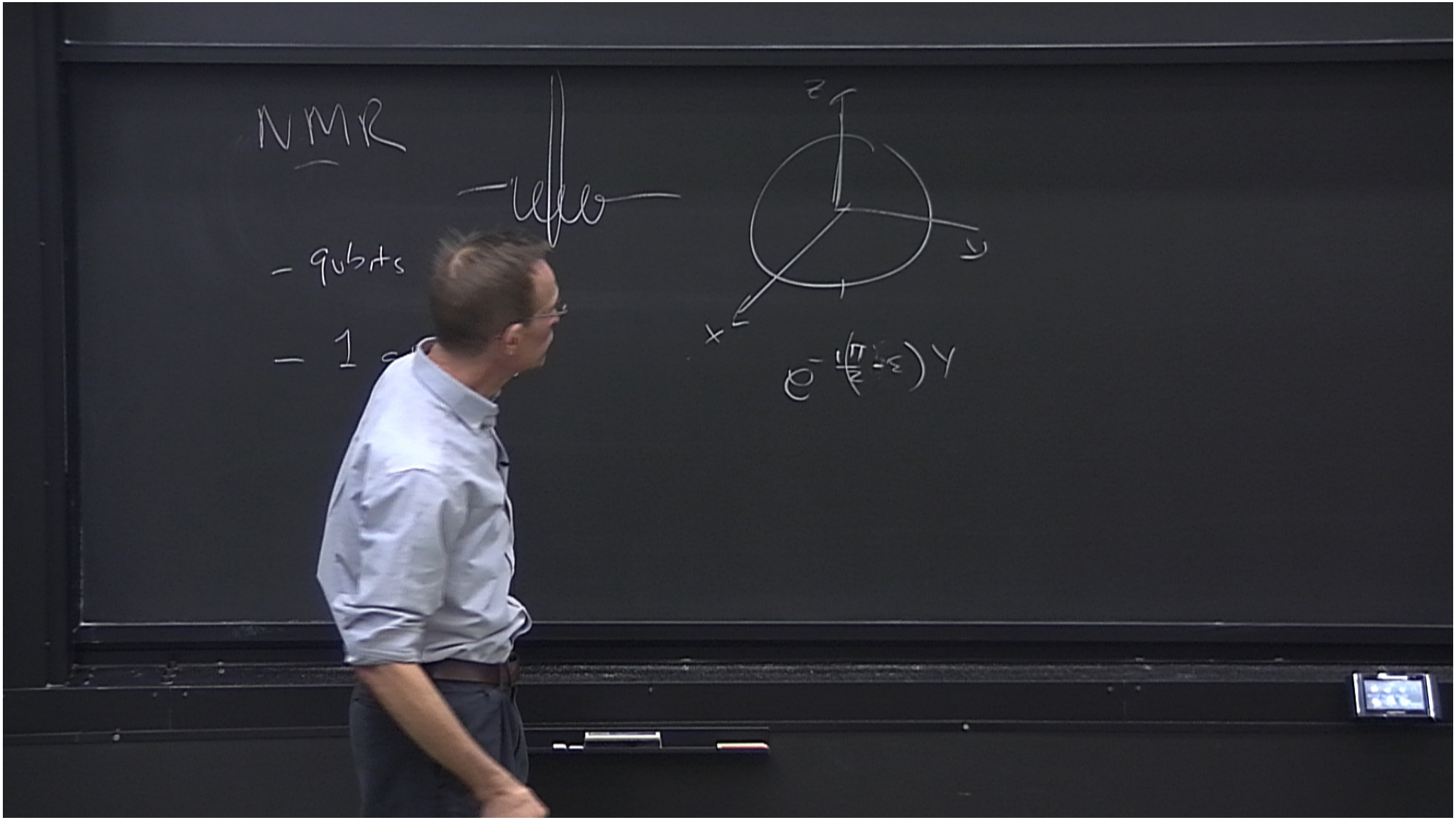
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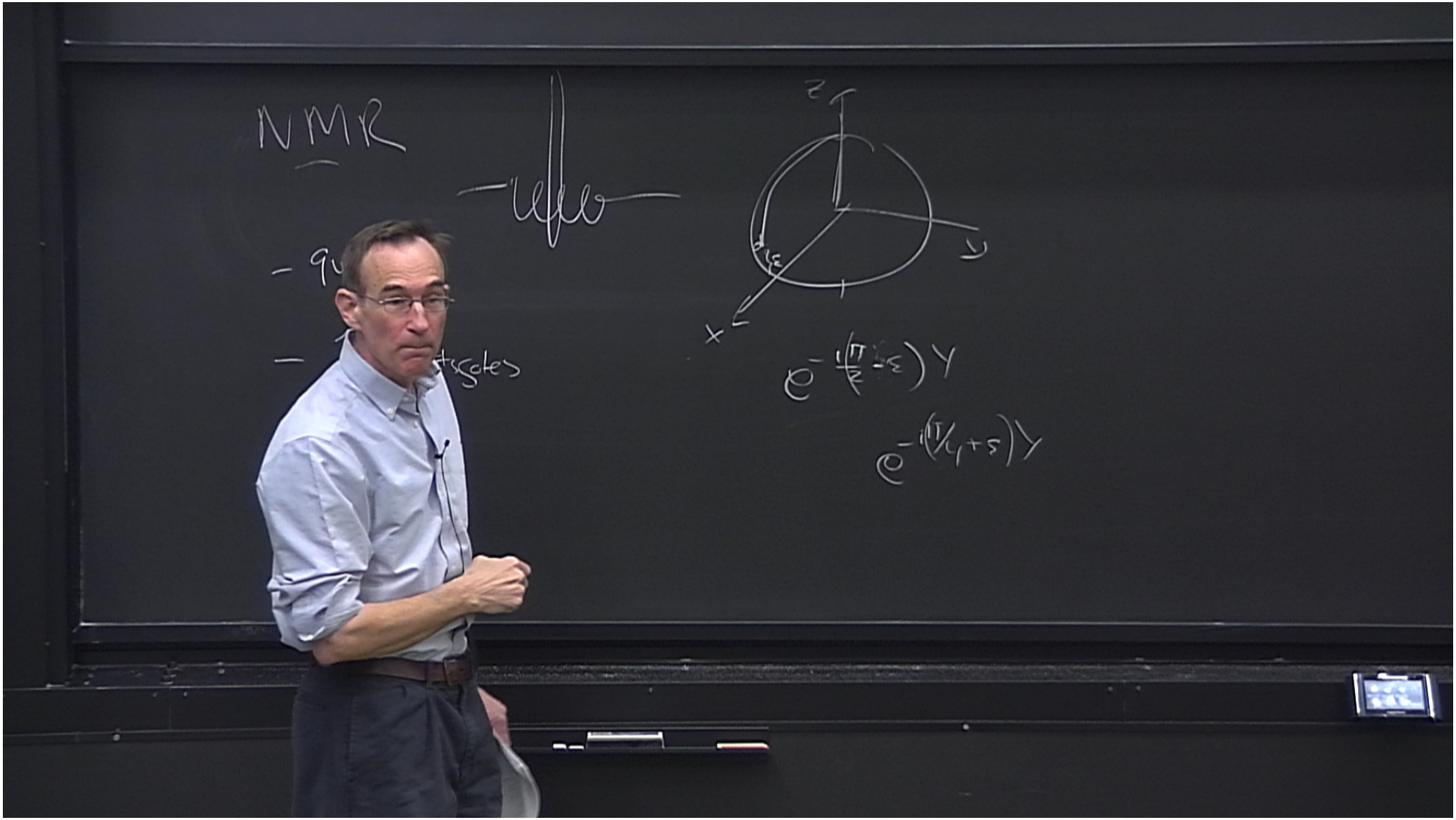
Abstract:

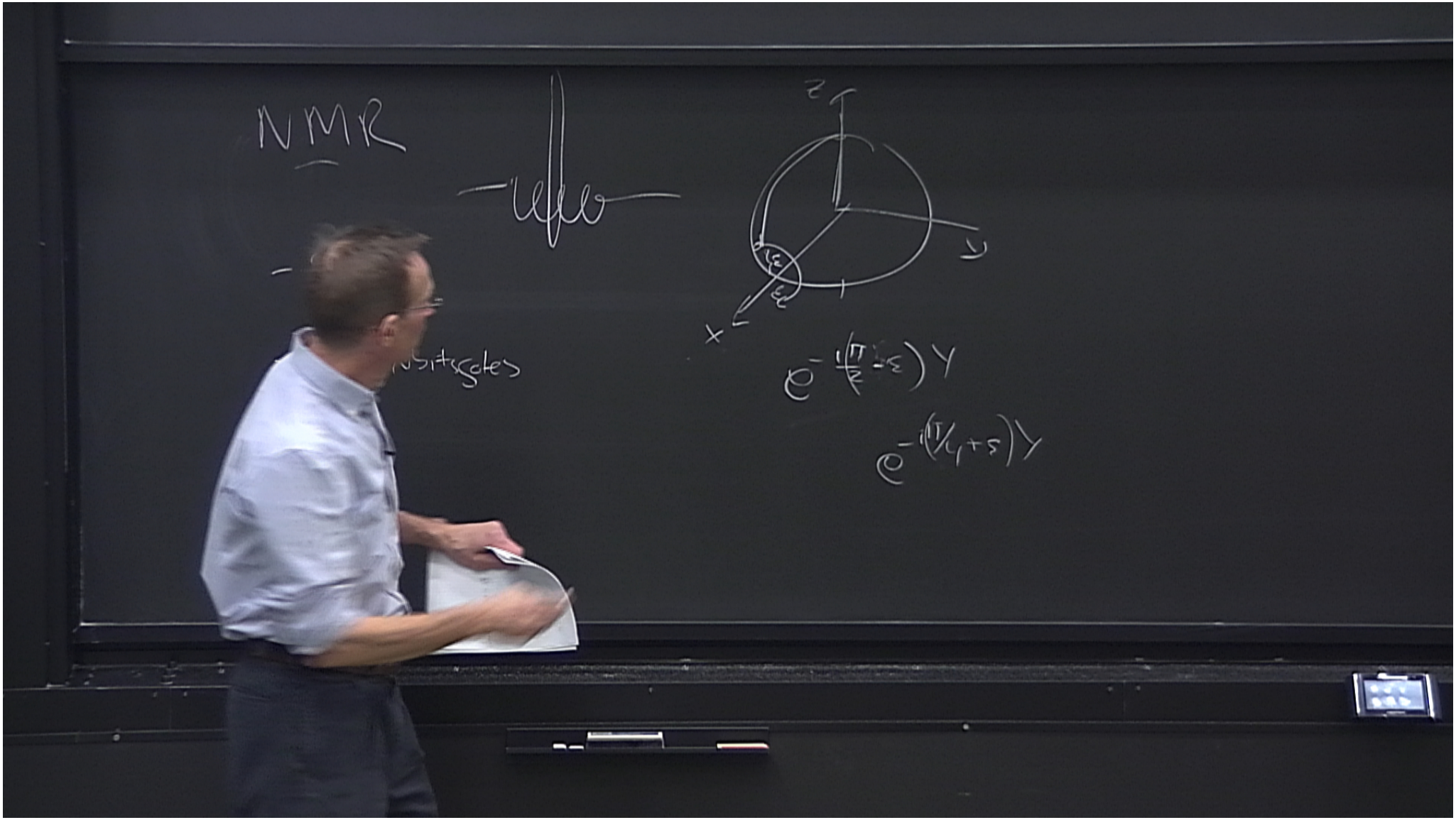

NMR

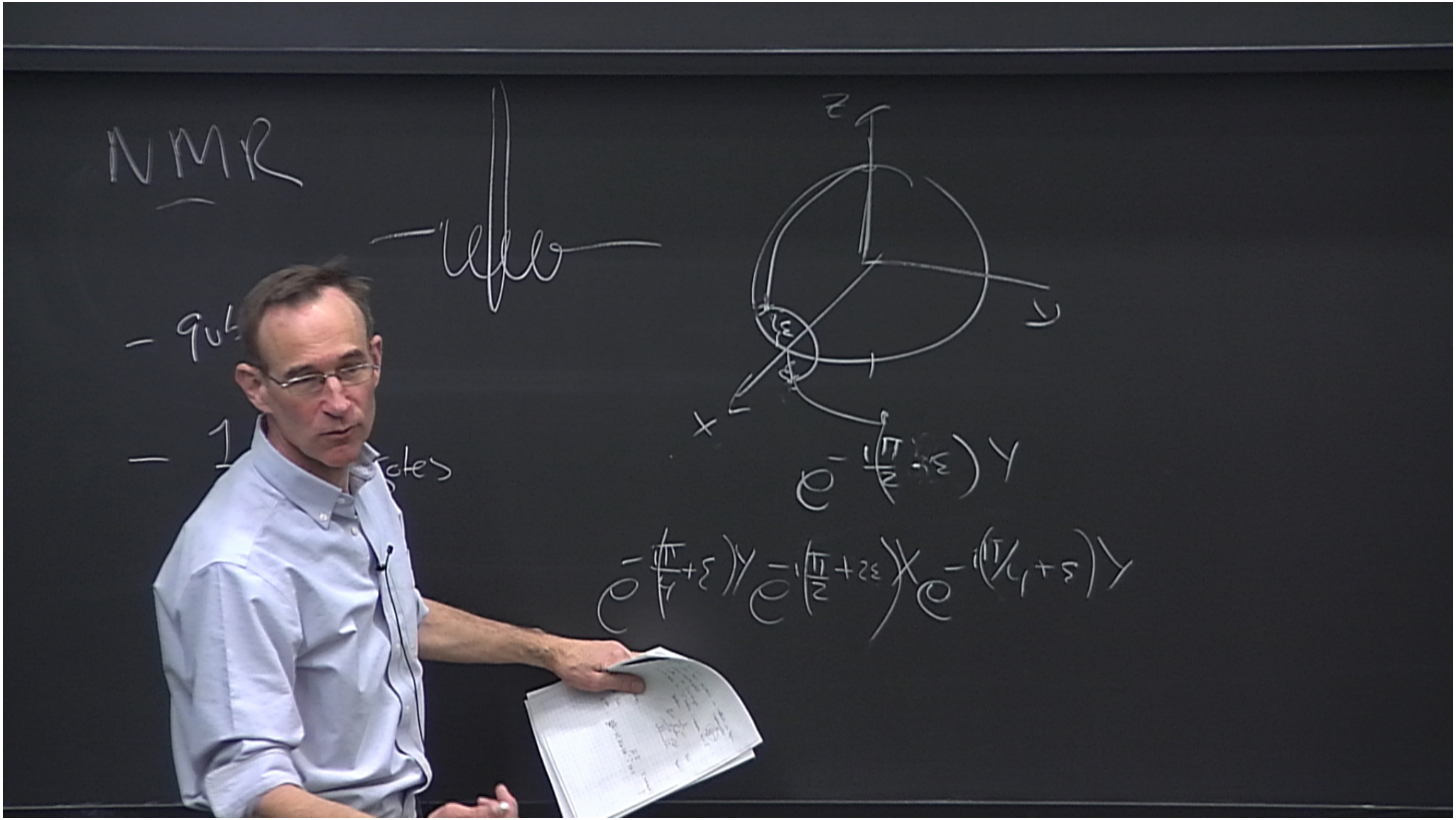

NMR
qubit gates
z
y
x

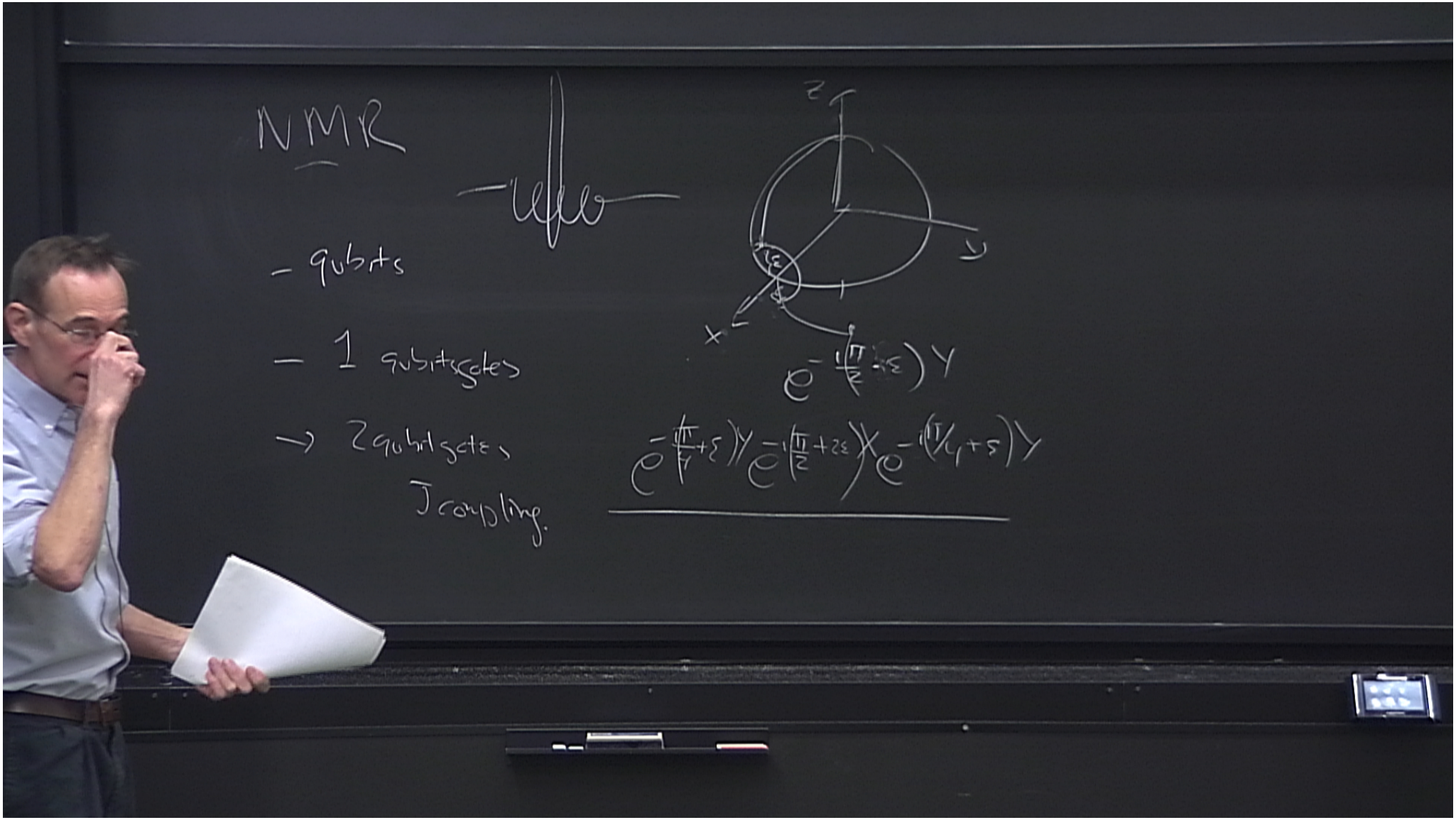

NMR
- qubits
- 1 qubit gates
z
y
x

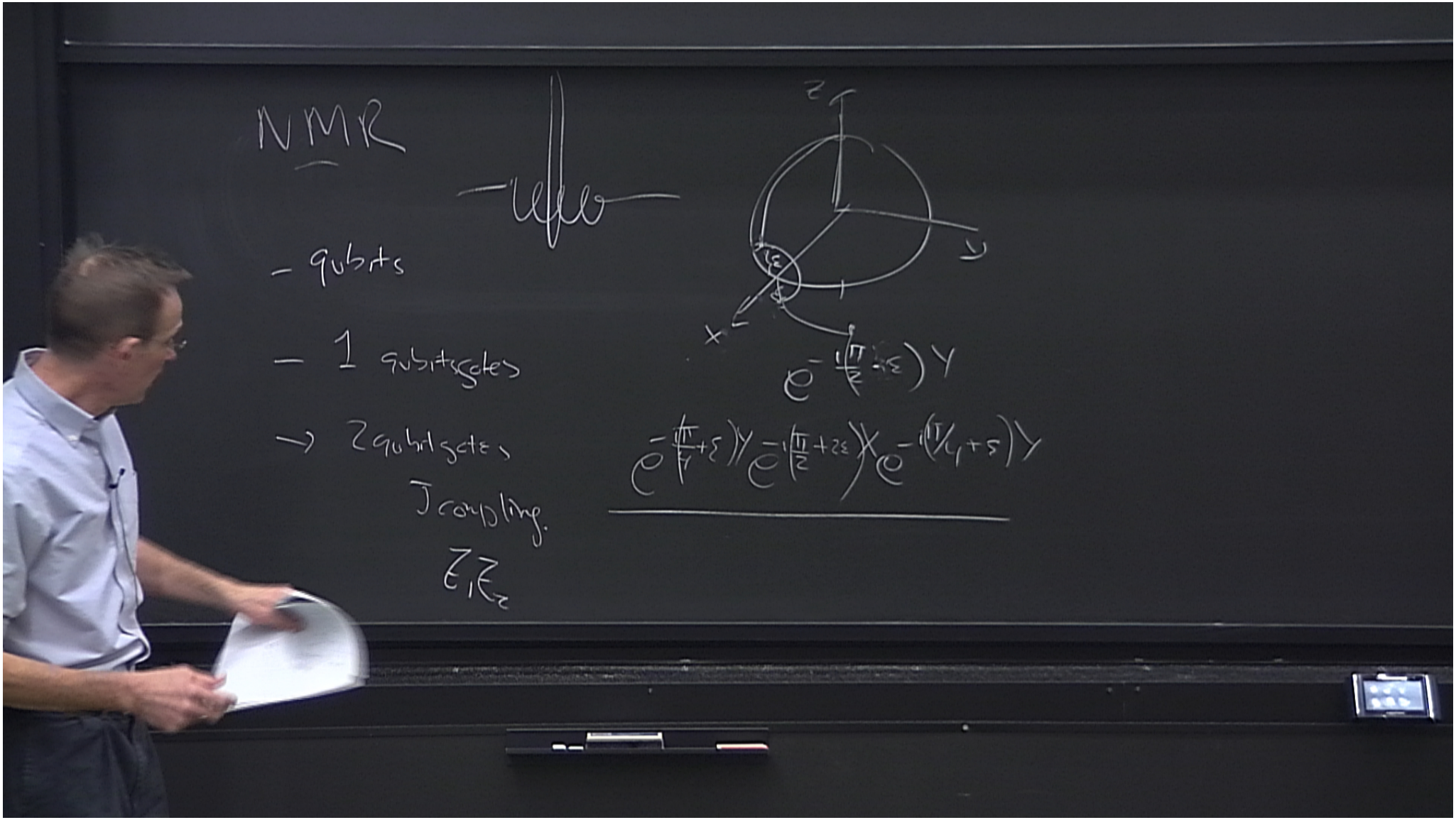

NMR
- qubits
- 1
z
y
x

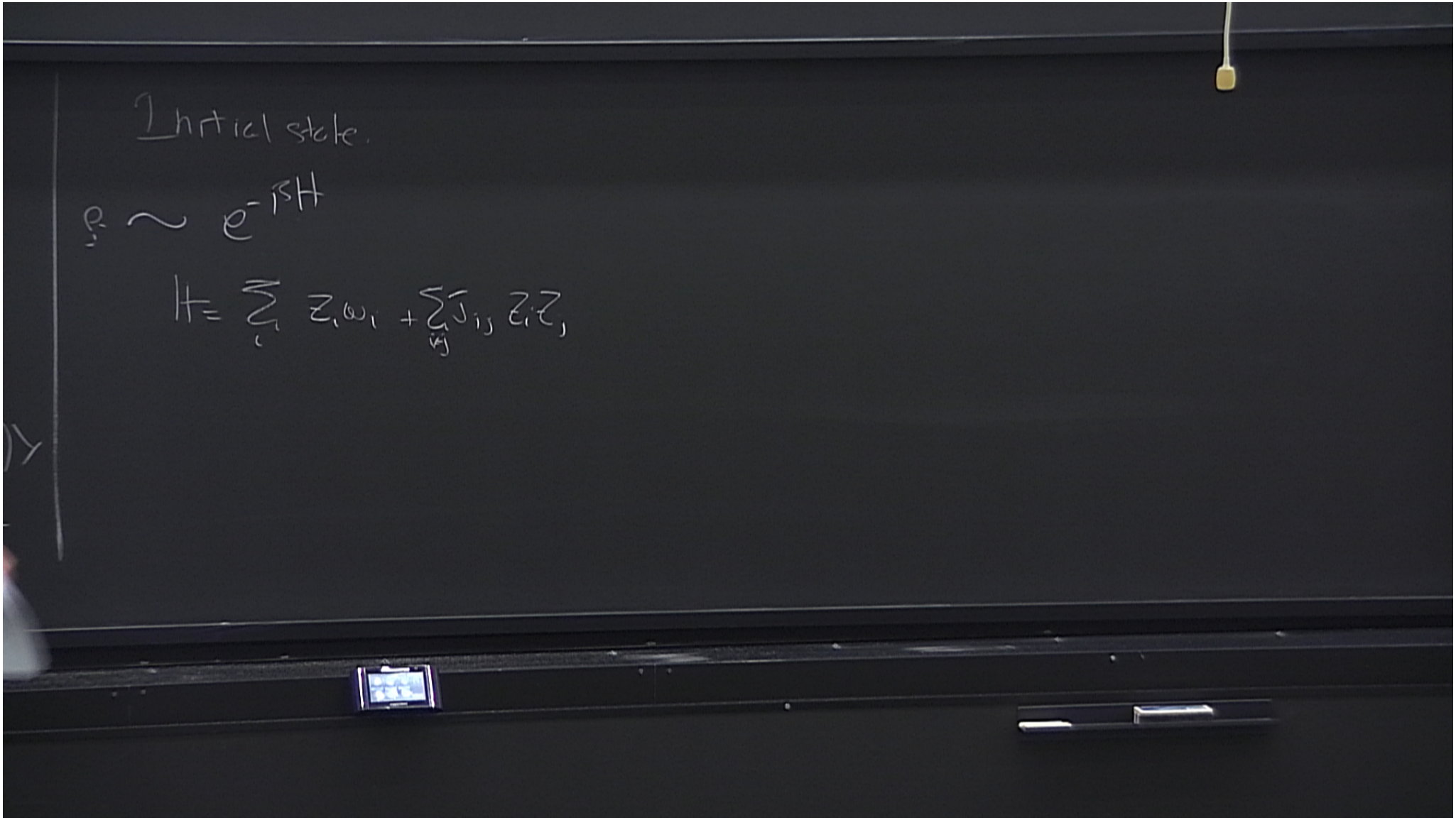

NMR
z
y
x

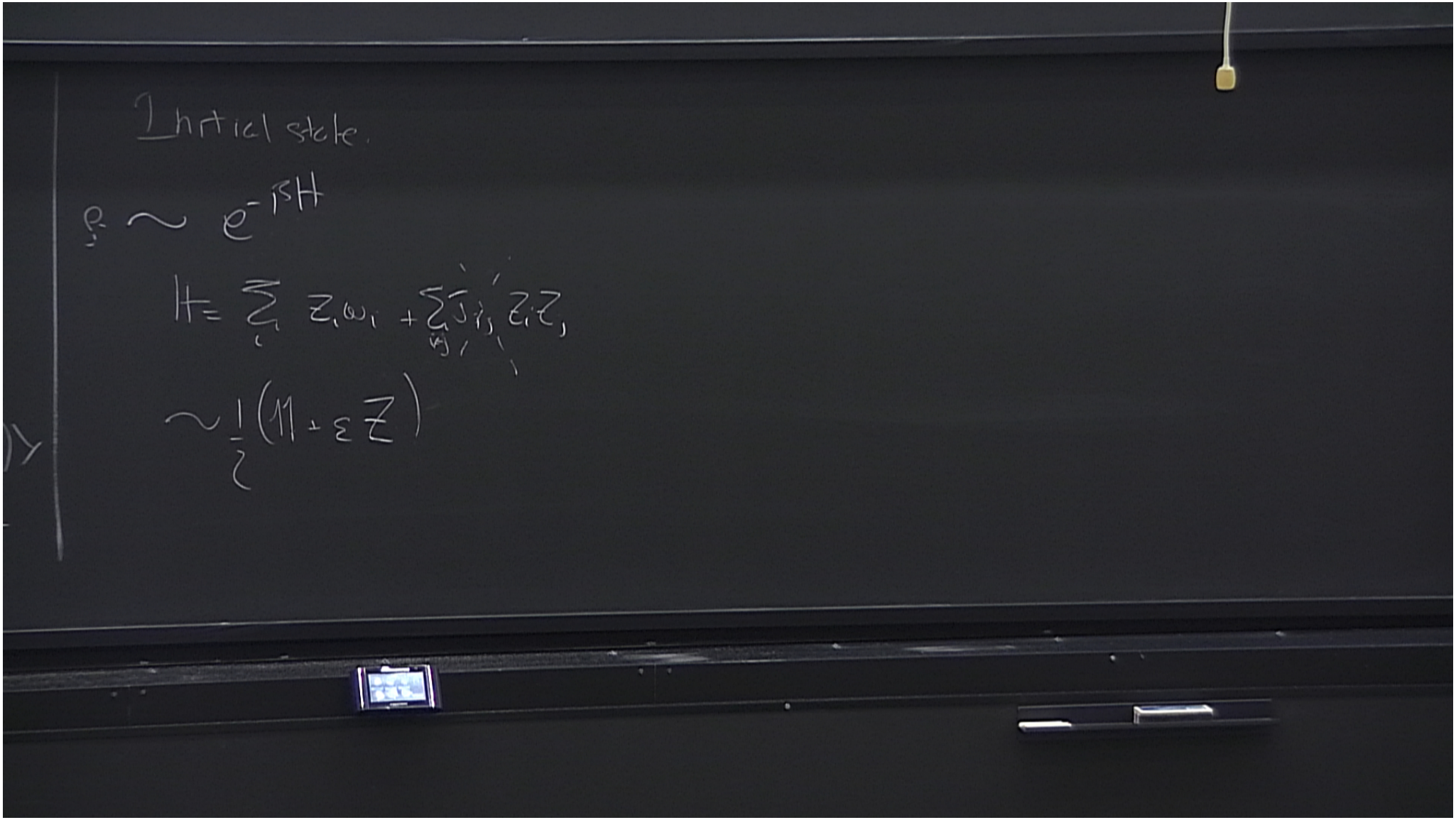

NMR
z
y
x

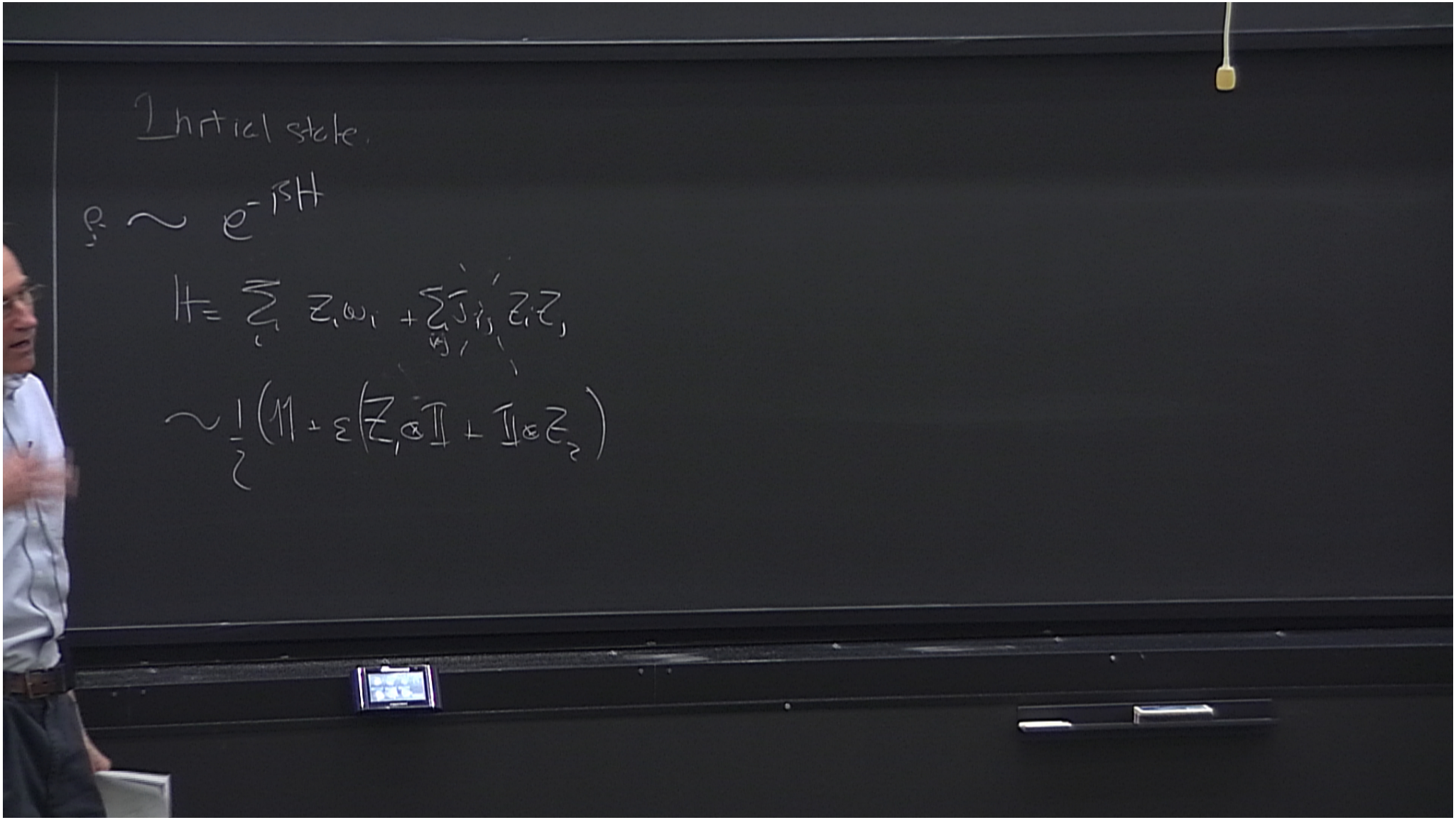

NMR
z
y
x

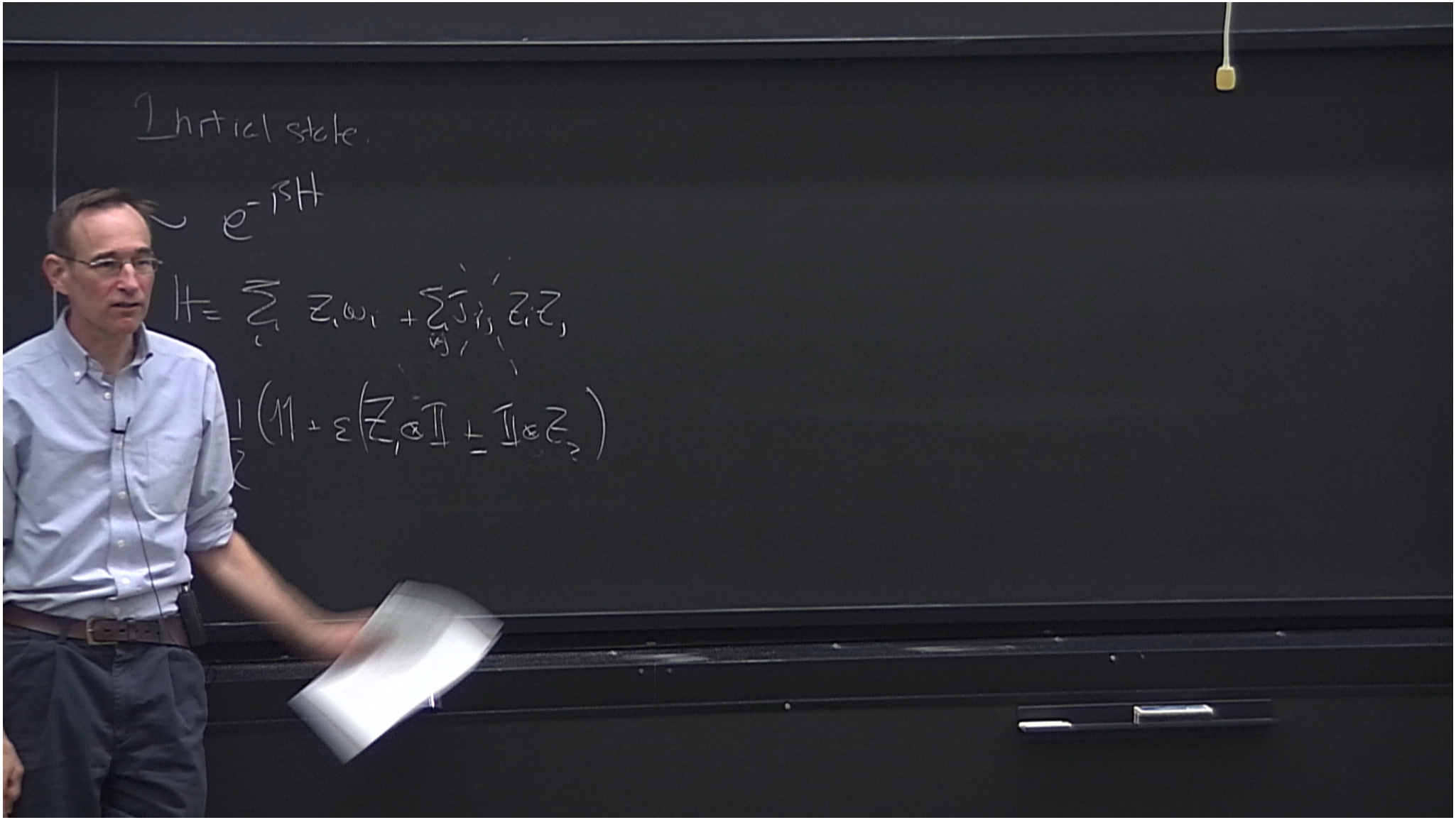

NMR
- qubits
- 1 qubit gates
→ 2 qubit gates
J coupling.
z
y
x

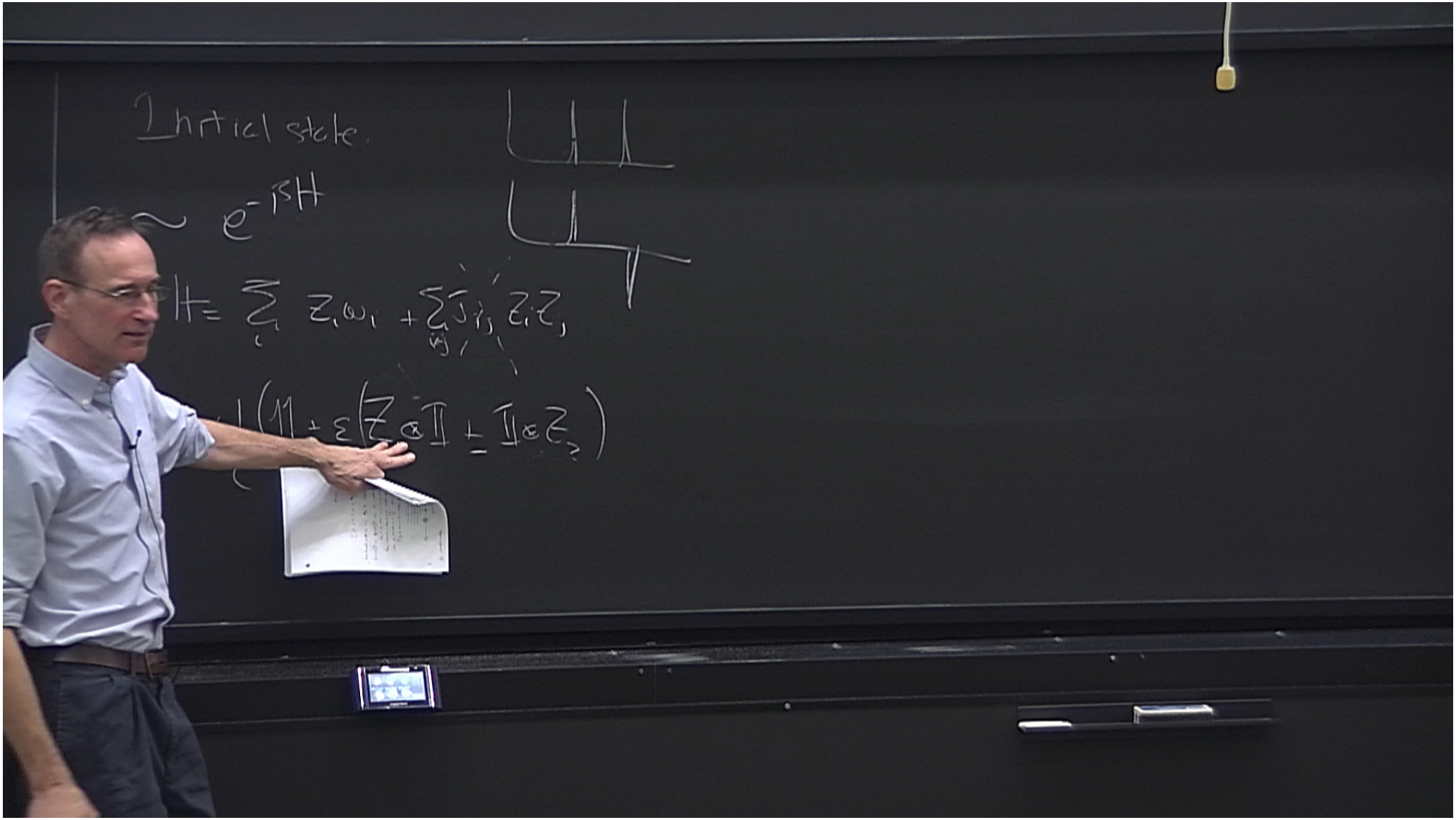

NMR
- qubits
- 1 qubit gates
→ 2 qubit gates
J coupling.
$Z_1 Z_2$
z
y
x

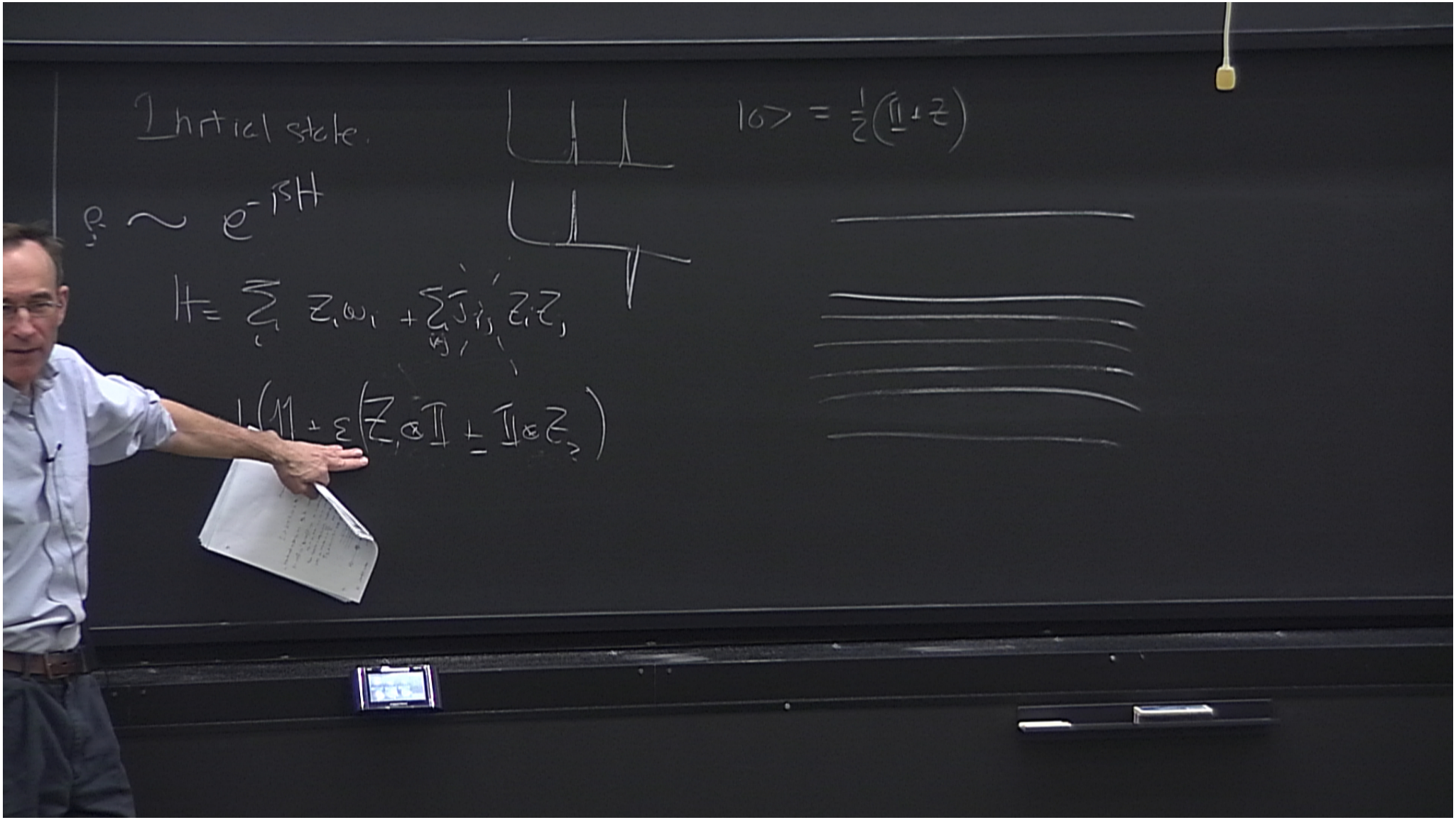

Initial state.
$\rho \sim e^{-\beta H}$
$H = \sum_i z_i \omega_i + \sum_{ij} J_{ij} z_i z_j$

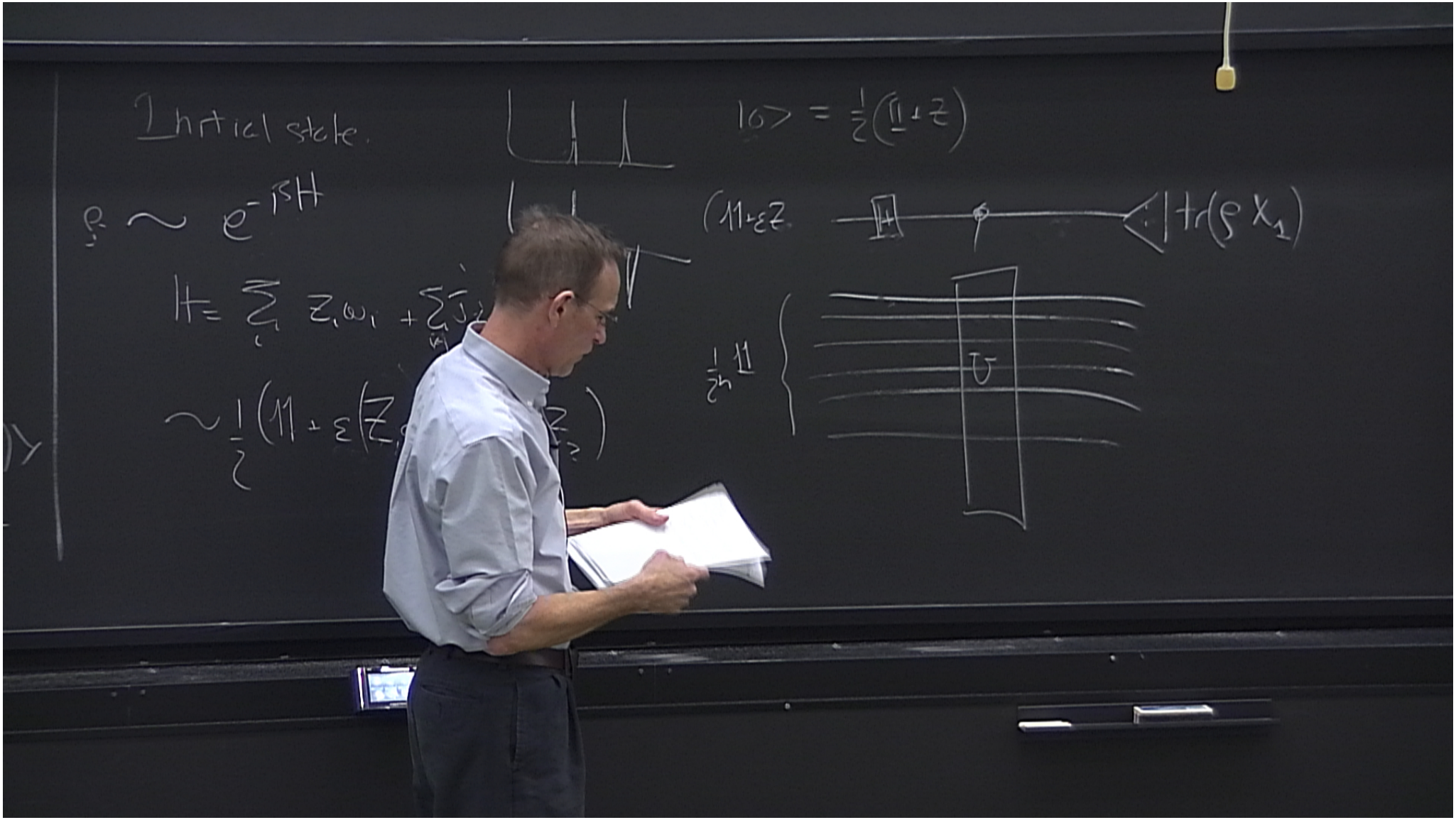

Thermal state.
$\rho \sim e^{-\beta H}$
$H = \sum_i z_i \omega_i + \sum_{ij} J_{ij} z_i z_j$
$\sim \frac{1}{2}(\mathbb{1} + \varepsilon Z)$

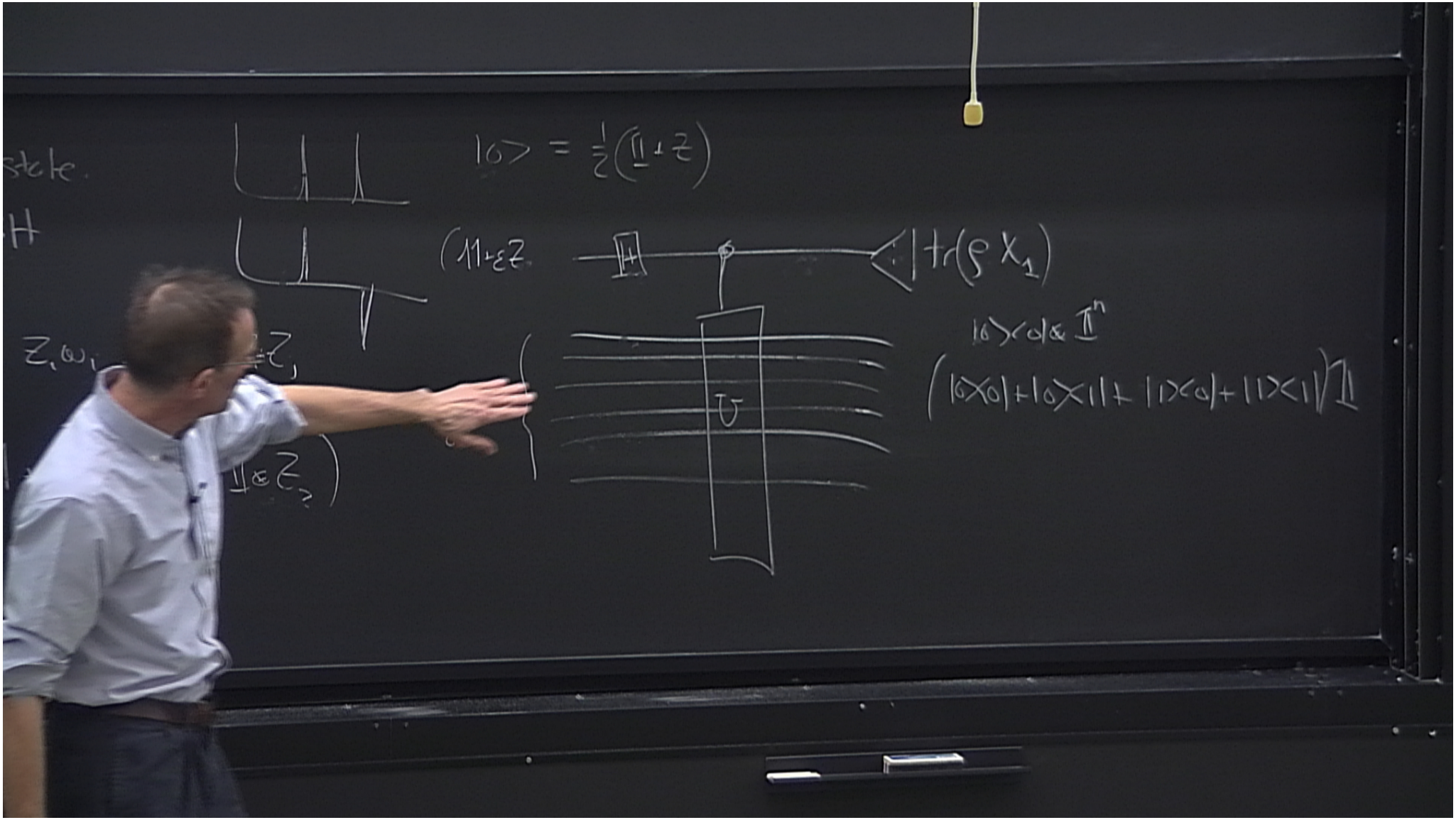

Initial state.
$\rho \sim e^{-\beta H}$
$H = \sum_i z_i \omega_i + \sum_{ij} J_{ij} z_i z_j$
$\sim \frac{1}{2}(\mathbb{1} + \varepsilon(Z_1 \otimes \mathbb{I} + \mathbb{I} \otimes Z_2))$

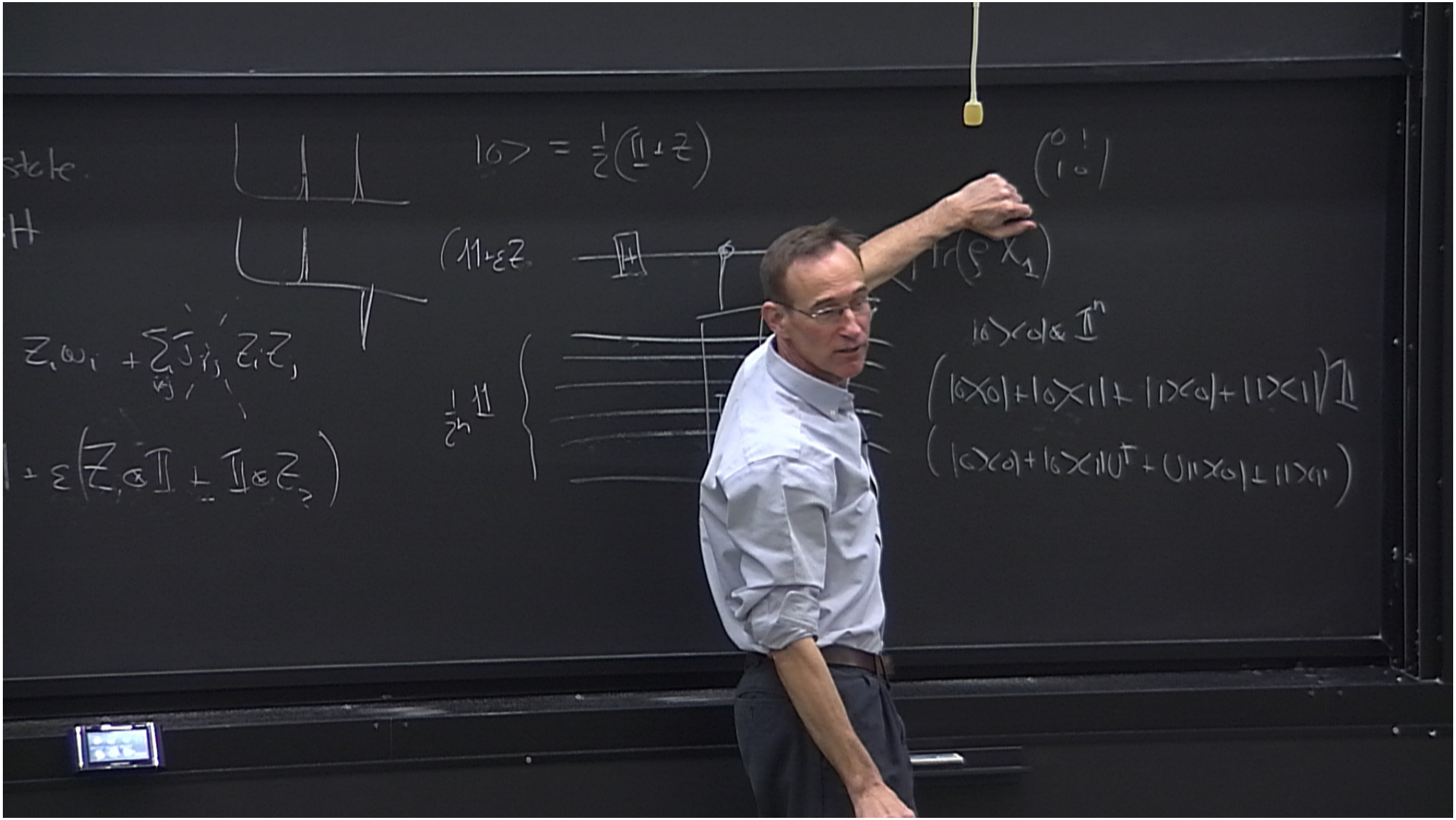

Initial state.
$\sim e^{-\beta H}$
$H = \sum_i z_i \omega_i + \sum_{ij} J_{ij} z_i z_j$
$\frac{1}{2}(11 + \varepsilon(Z_1 \otimes \mathbb{I} \pm \mathbb{I} \otimes Z_2))$

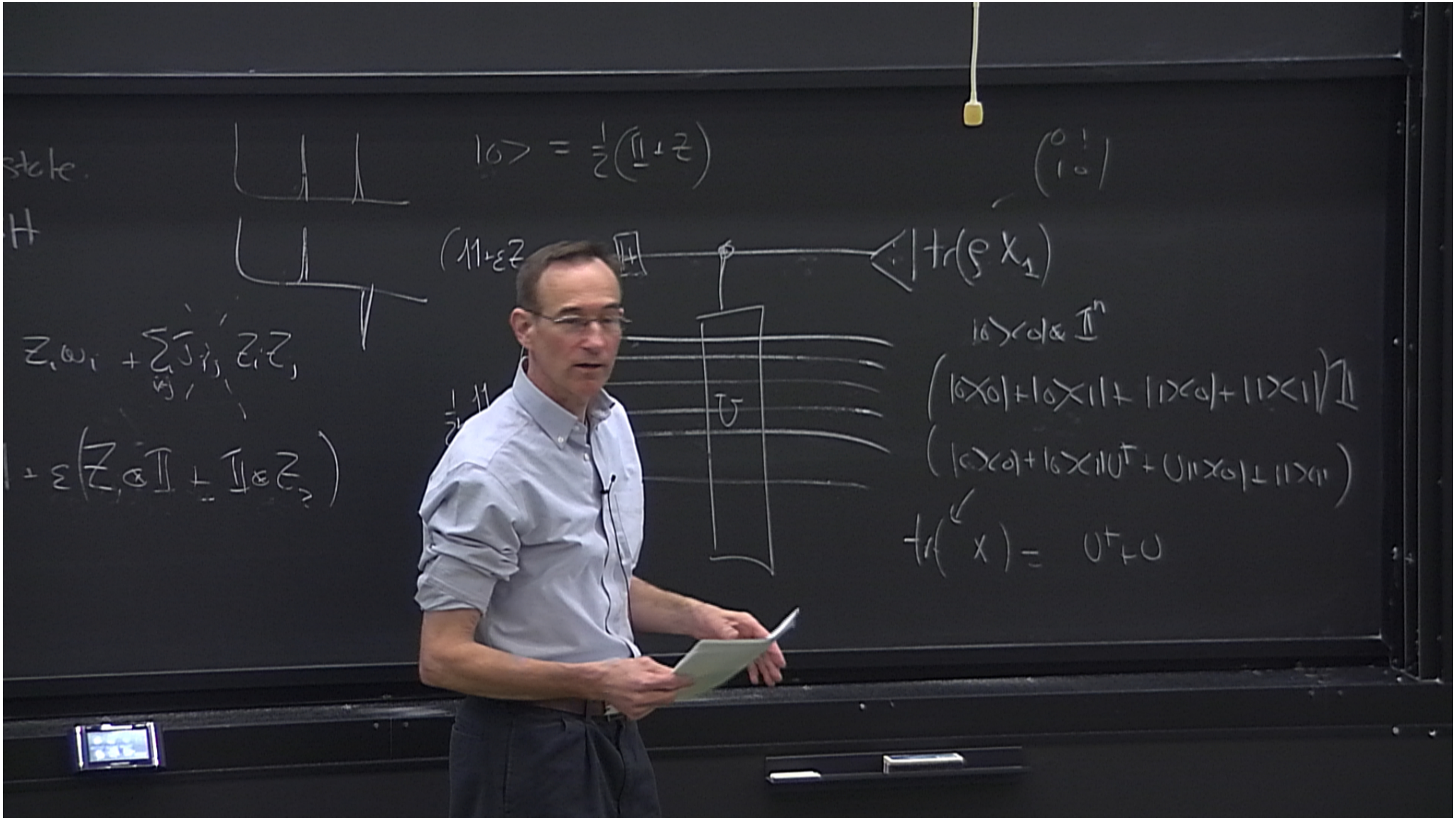

Initial state.
$\sim e^{-\beta H}$
$H = \sum_i z_i \omega_i + \sum_{ij} J_{ij} z_i z_j$
$(\mathbb{1} + \varepsilon(Z \otimes \mathbb{1} \pm \mathbb{1} \otimes Z))$

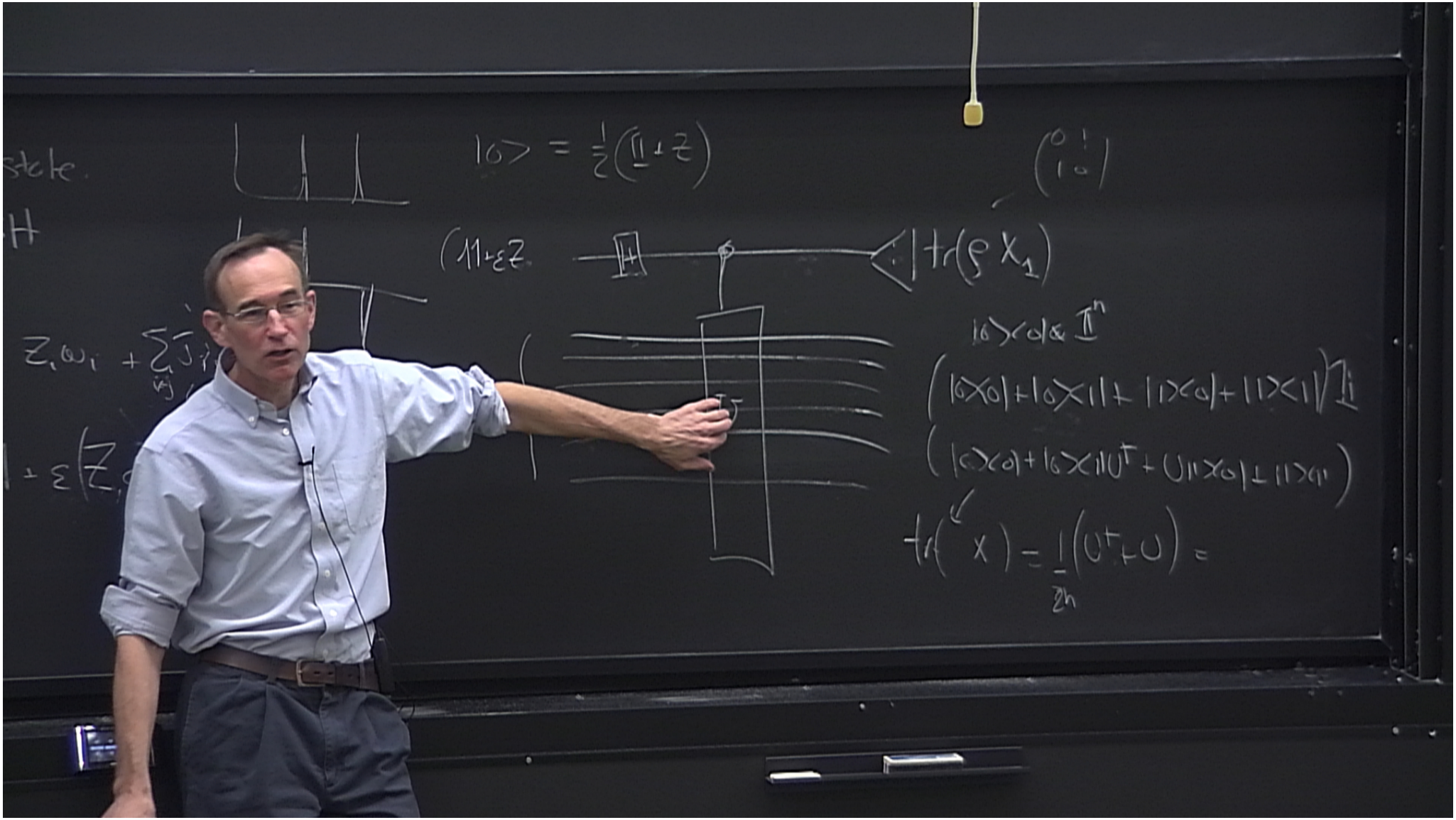

Initial state.
$\rho \sim e^{-\beta H}$
$H = \sum_i z_i \omega_i + \sum_{ij} J_{ij} z_i z_j$
$|0\rangle = \frac{1}{2}(\mathbb{1} + z)$

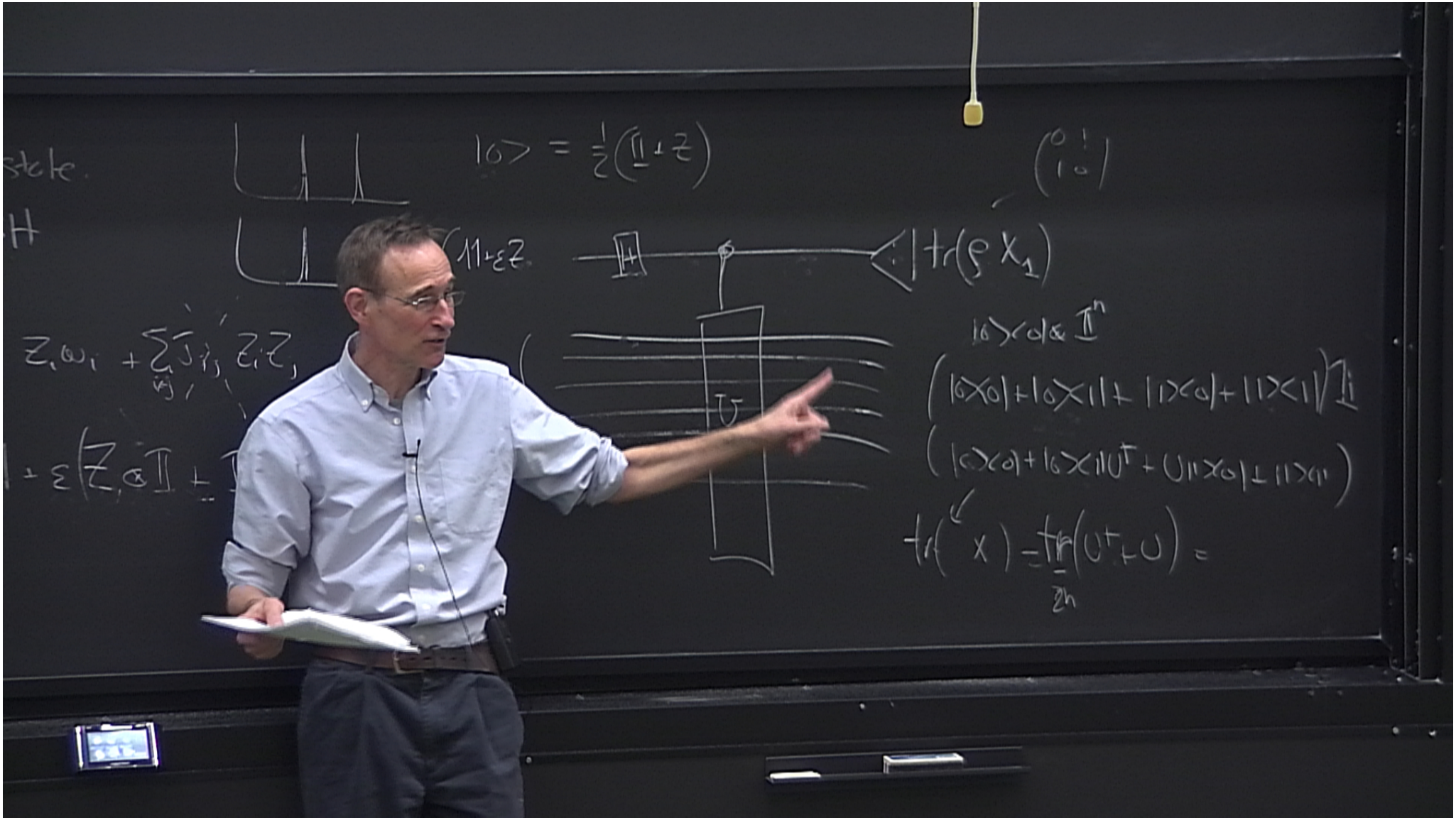

Initial state.
$|0\rangle = \frac{1}{2}(\mathbb{1} + Z)$
$\rho \sim e^{-\beta H}$
$H = \sum_i z_i \omega_i + \sum_{ij} J_{ij}$
$\sim \frac{1}{2}(\mathbb{1} + \varepsilon(Z$
$(\mathbb{1} + \varepsilon Z$
$\mathrm{tr}(\rho X_1)$
$\frac{1}{2^n}\mathbb{1}$
U

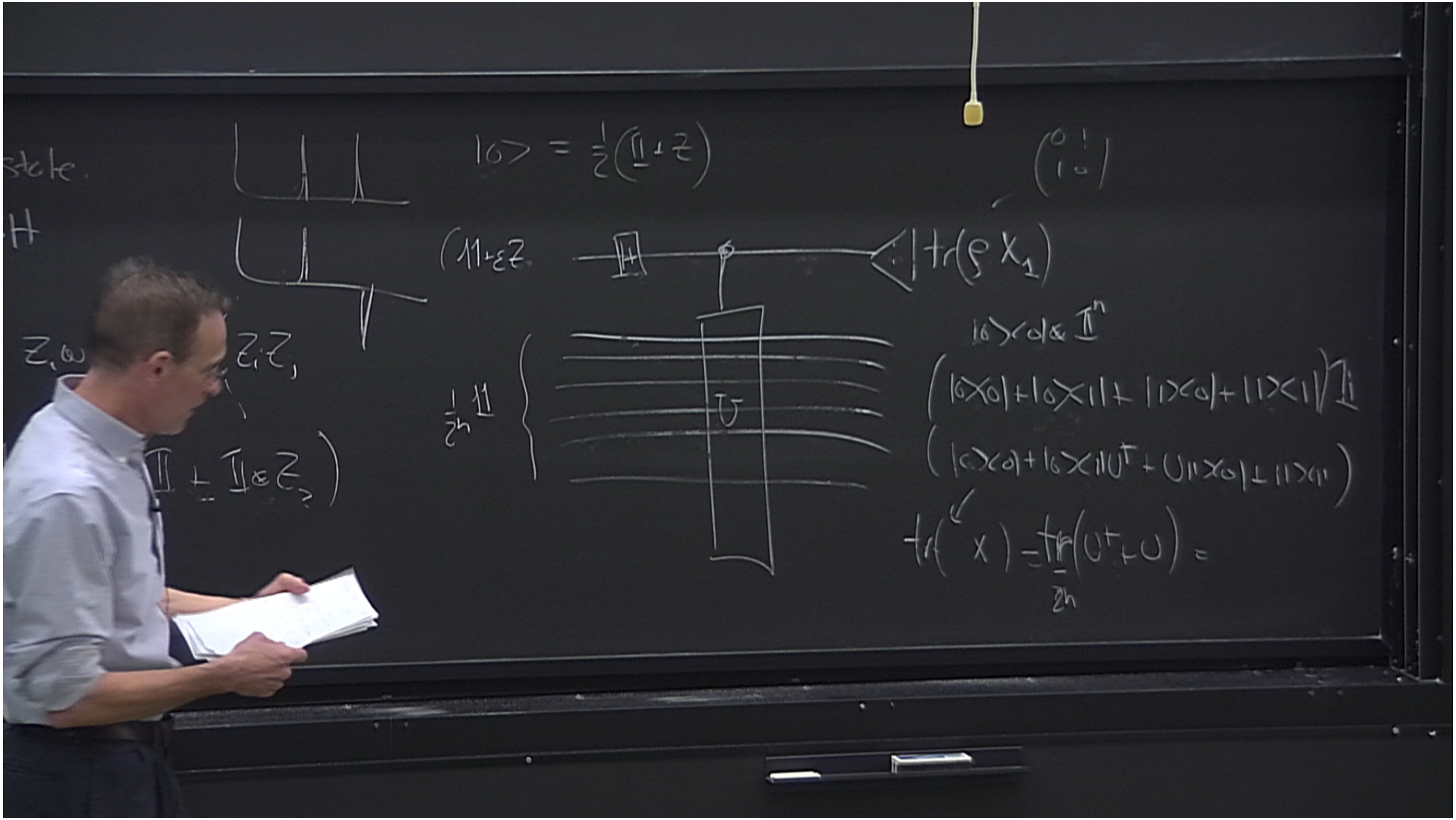

|0> = 1/2 (11 + Z)
(11 + εZ
tr(ρ X_1)
|0><0| ⊗ 11^n
(|0><0| + |0><1| + |1><0| + |1><1|)/11
U

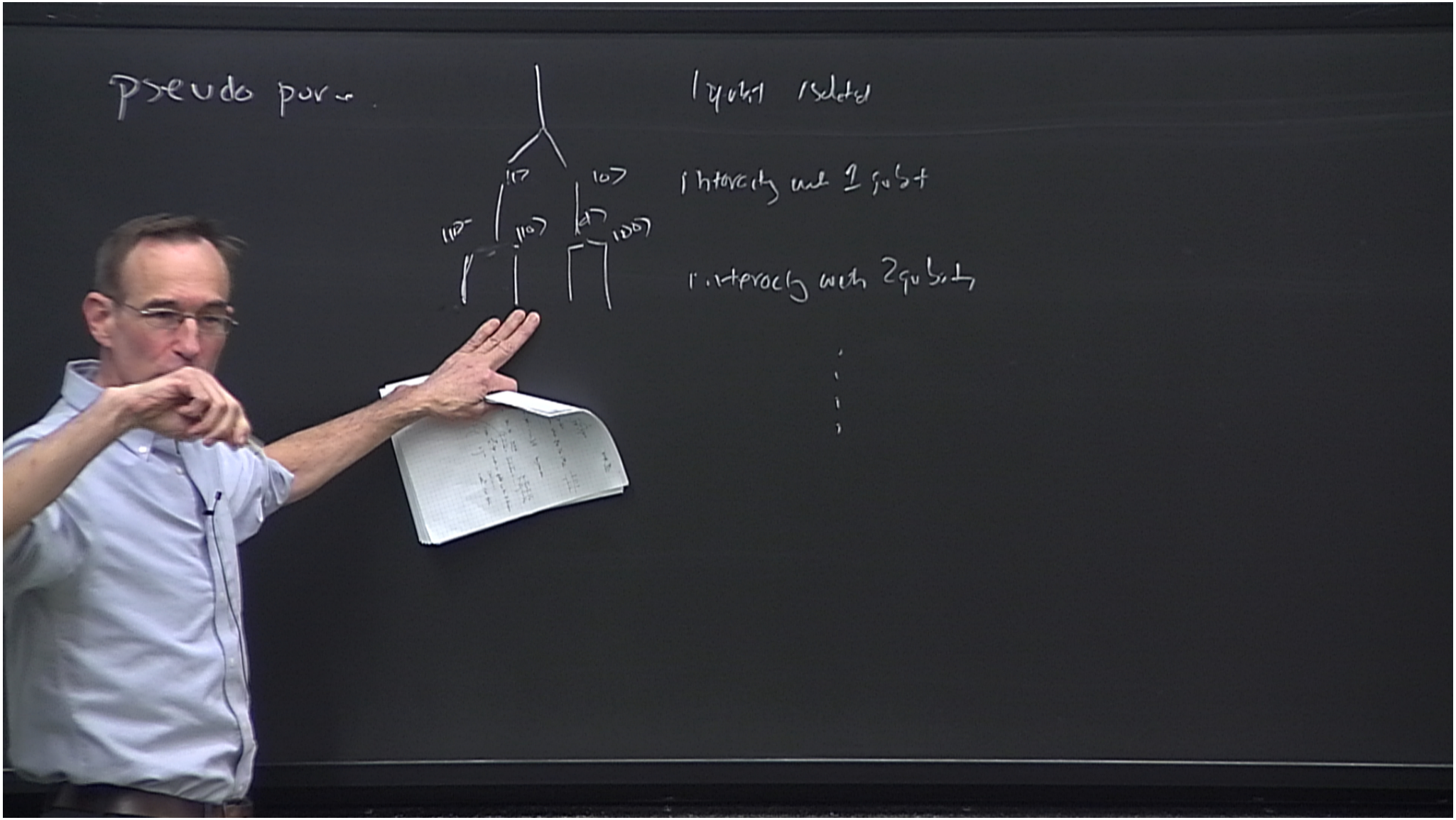

|0> = 1/2 (Π + Z)
|0><0| ⊗ Π^n
(|0><0| + |0><1| + |1><0| + |1><1|)/Π
(|0><0| + |0><1|U† + U|1><0| + |1><1|)

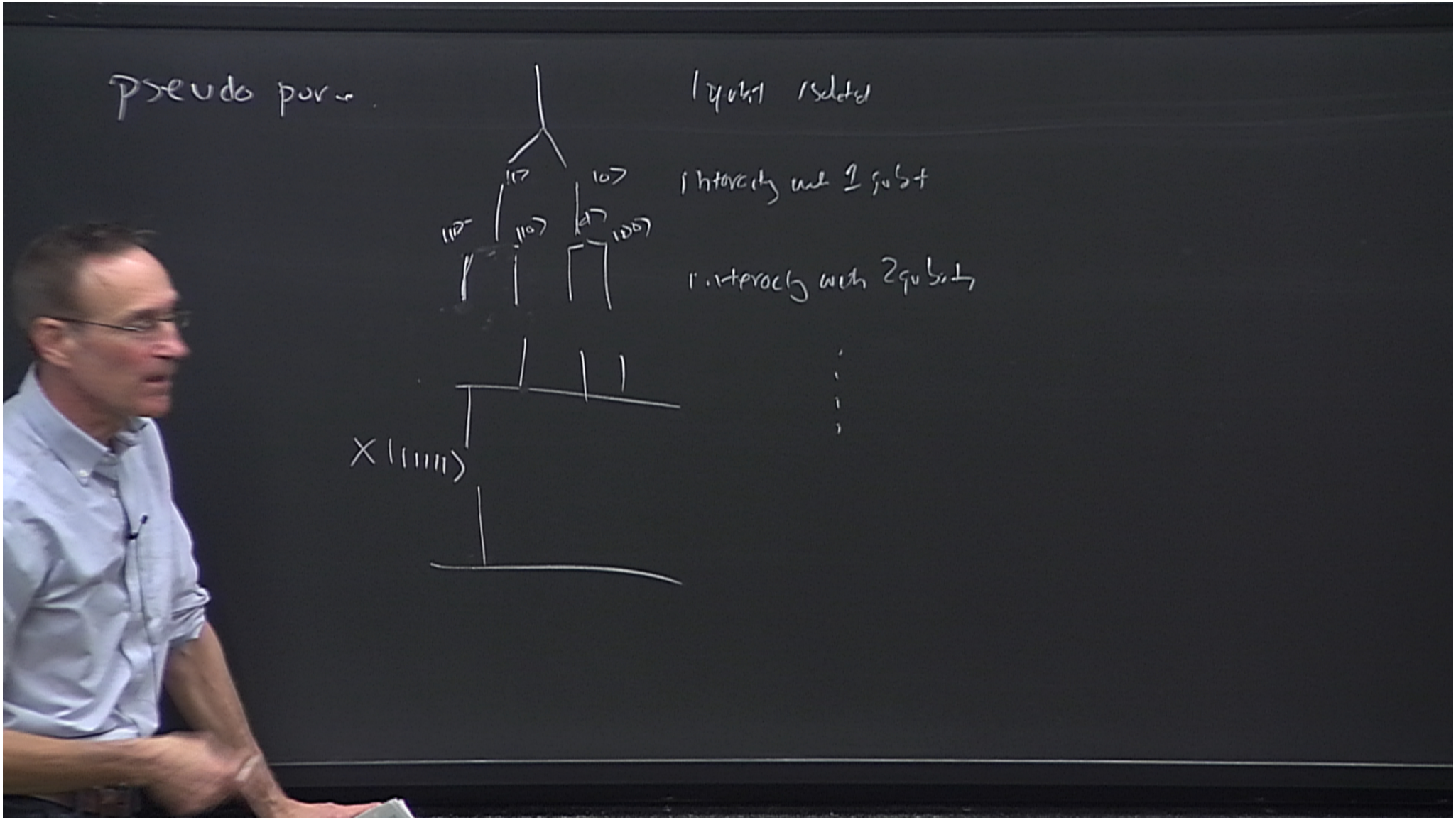

state.
H
$|0\rangle = \frac{1}{2}(\mathbb{1}+Z)$
$\left(\begin{smallmatrix}0 & 1\\ 1 & 0\end{smallmatrix}\right)$
$(\mathbb{1}+\varepsilon Z$
$\mathrm{tr}(\rho X_1)$
$|0\rangle\langle 0| \otimes \mathbb{1}^n$
$(|0\rangle\langle 0| + |0\rangle\langle 1| + |1\rangle\langle 0| + |1\rangle\langle 1|)/\mathbb{1}$
$(|0\rangle\langle 0| + |0\rangle\langle 1| U^\dagger + U|1\rangle\langle 0| + |1\rangle\langle 1|)$
$\mathrm{tr}(X) = U^\dagger + U$
$+\varepsilon(Z_1 \otimes \mathbb{1} + \mathbb{1} \otimes Z_2)$
U

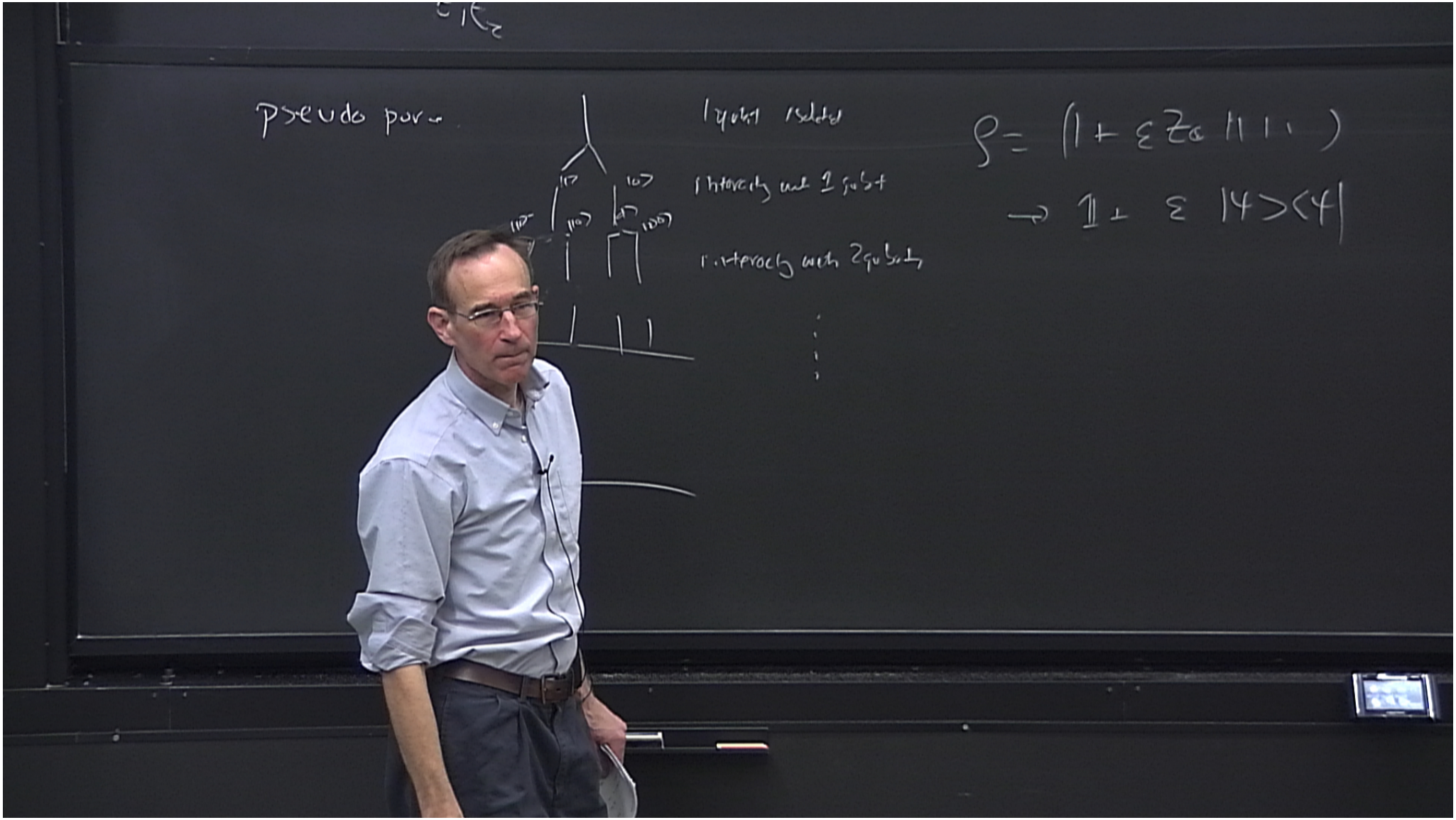

|0> = 1/2 (11 + Z)
tr(ρ X_1)
|0><0| ⊗ 11^n
(|0><0| + |0><1| + |1><0| + |1><1|)^⊗n
(|0><0| + |0><1|U^T + U|1><0| + |1><1|)
tr(X) = 1/2n (U^T + U) =

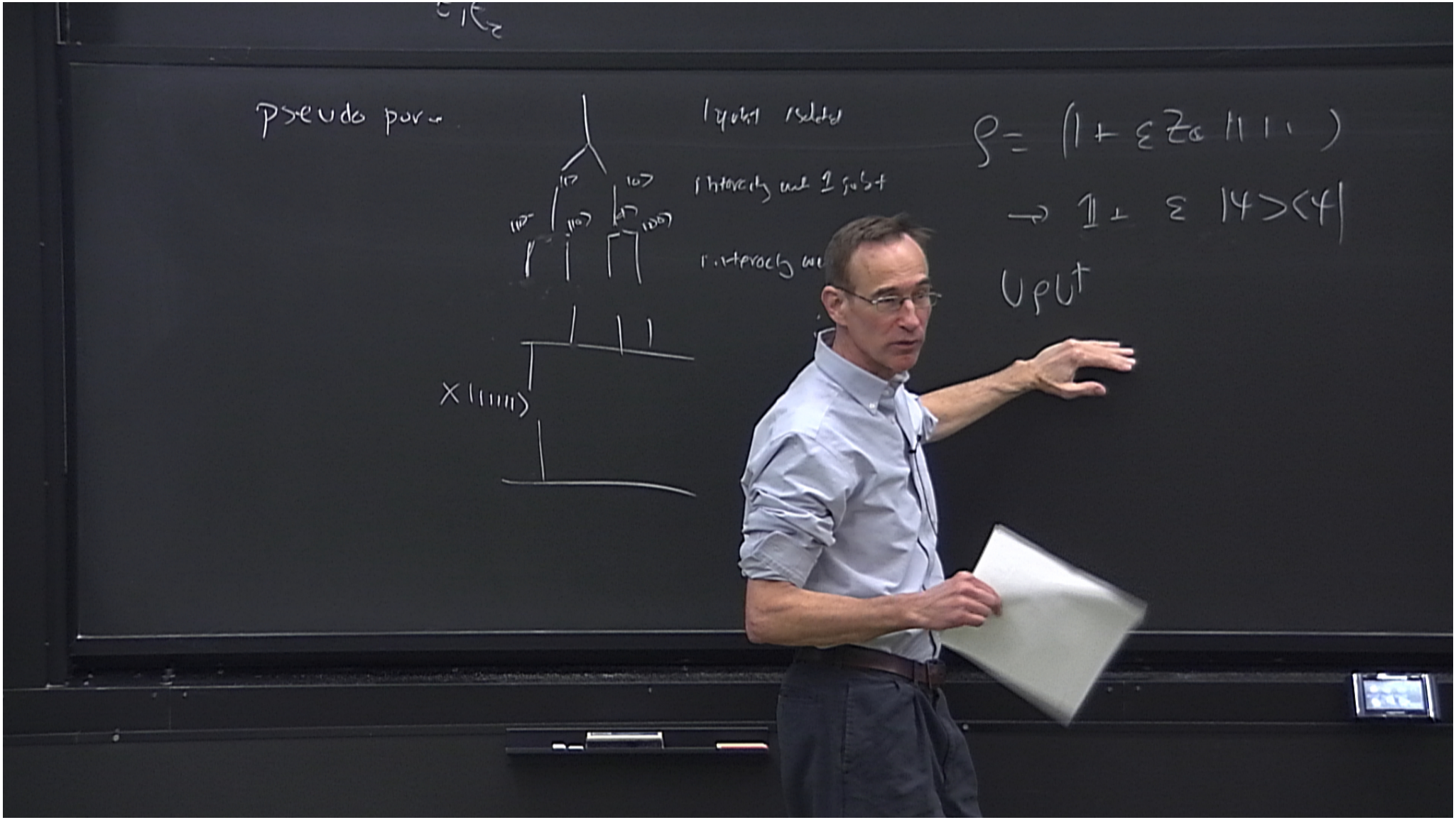

|0> = 1/2 (11 + Z)
tr(ρ X_1)
|0><0| ⊗ 11^n
tr(X) = tr(U^+ U) =
2n

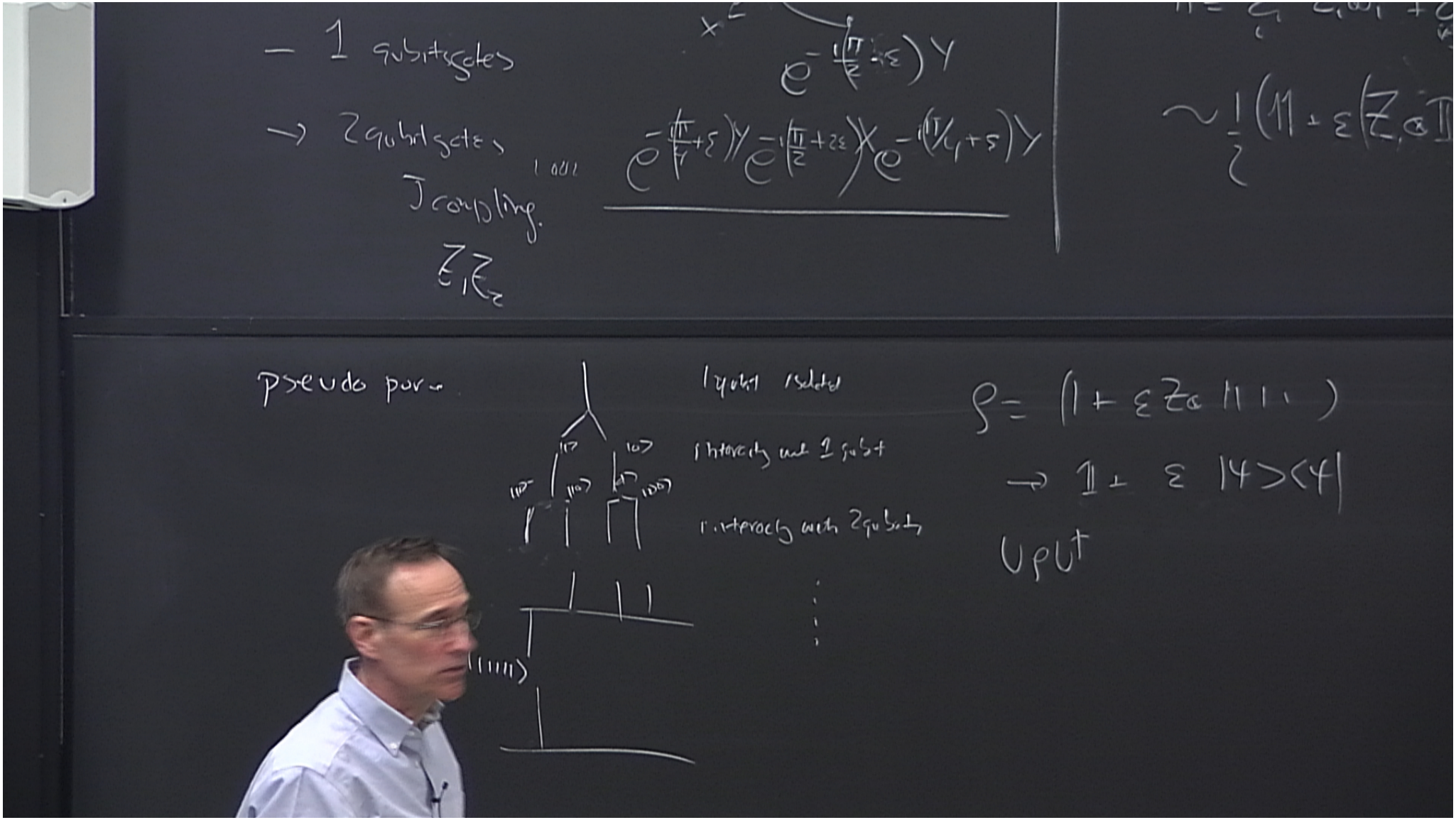

|0> = 1/2 (11 + Z)
tr(ρ X_1)
|0><0| ⊗ 11^n
U
tr(X) = tr(U^+ U) =

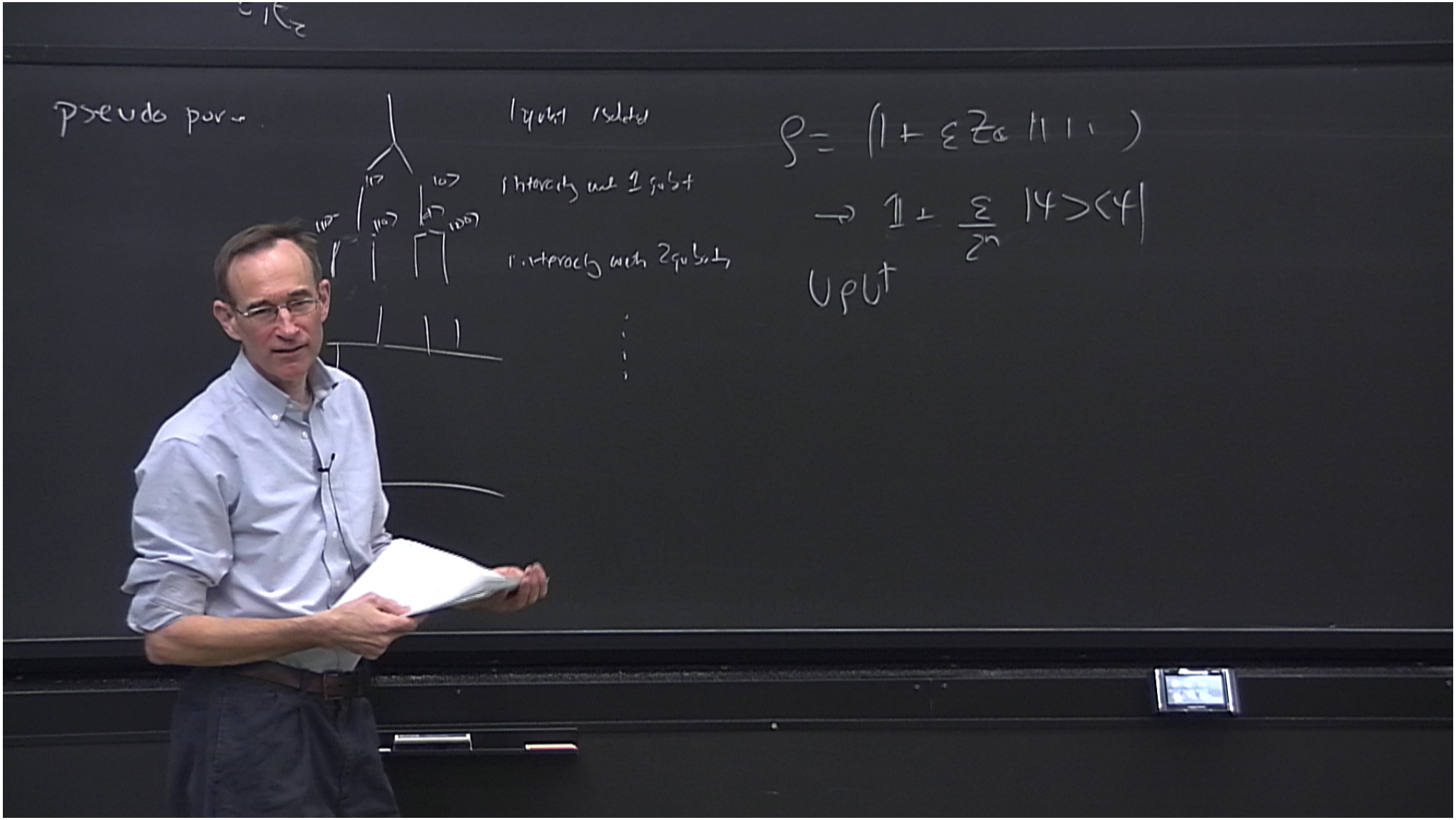

pseudo pure
|111⟩
|101⟩
|110⟩
|100⟩
|001⟩
|000⟩
1 qubit isolated
interacts with 1 qubit
interacts with 2 qubits

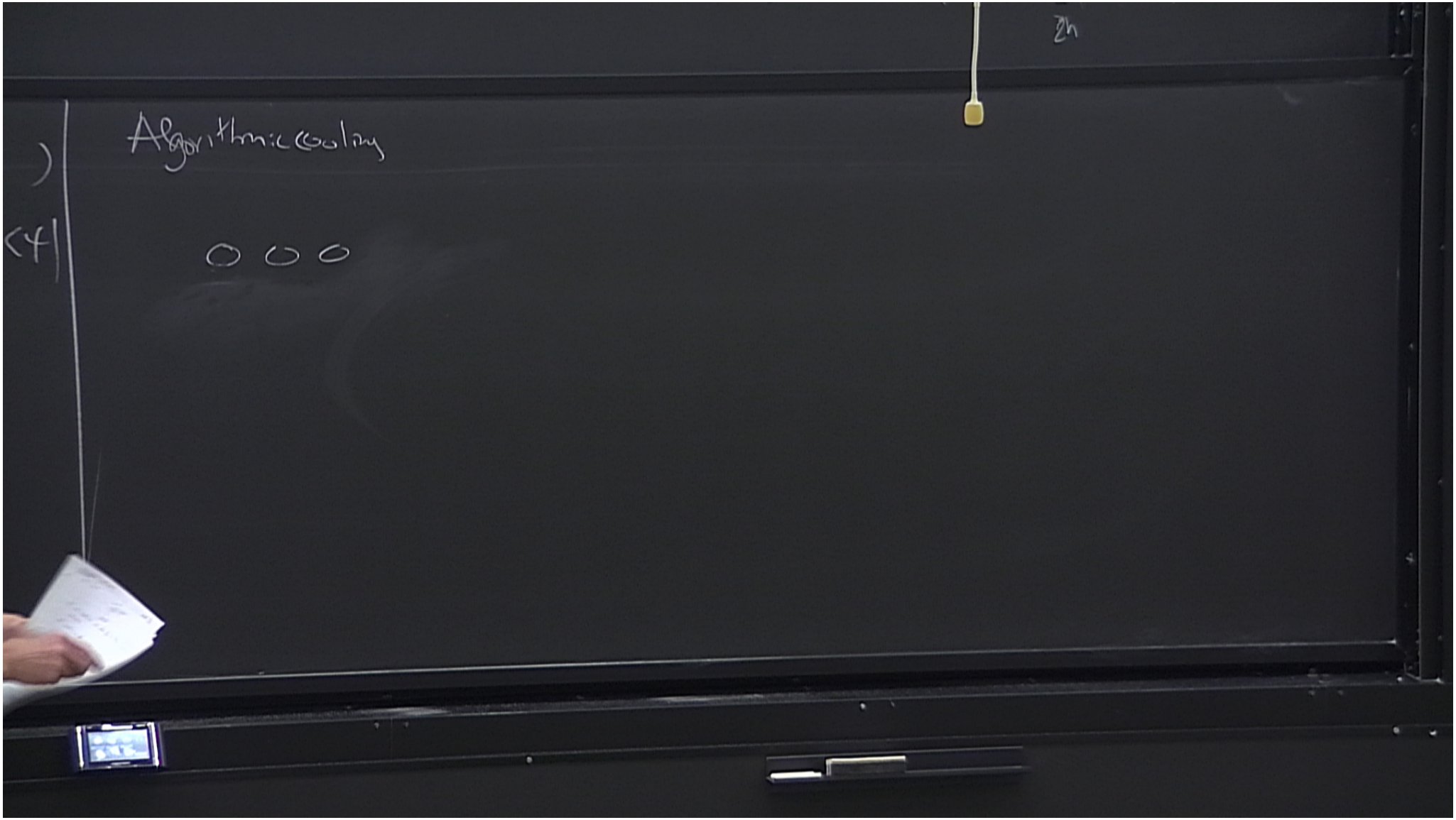

pseudo pure
|qubit isolated
|0⟩
|0⟩
interacts with 1 qubit
|0⟩
|0⟩
|0⟩
|00⟩
interacts with 2 qubits
X|11111⟩

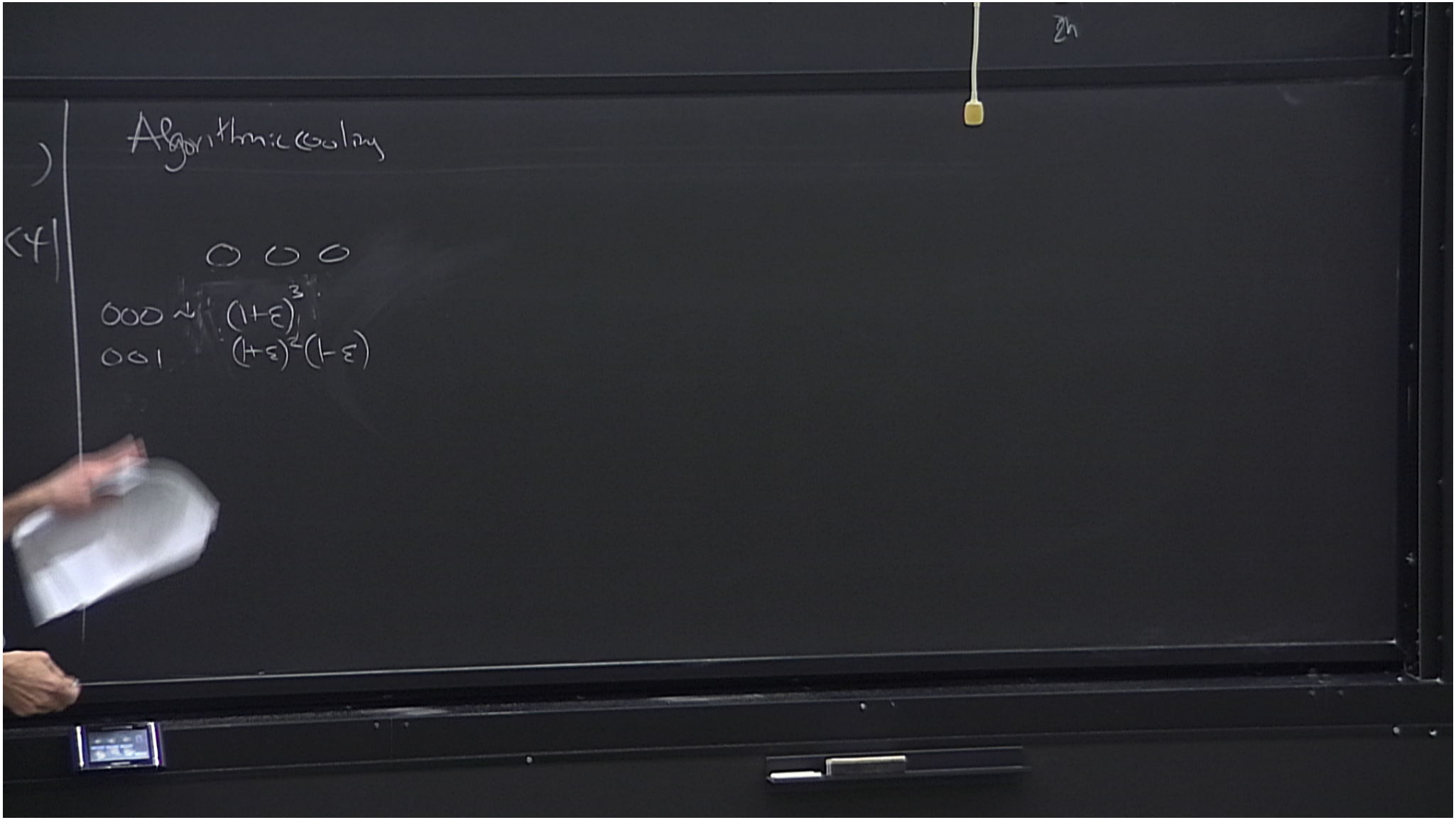

pseudo pure
1 qubit isolated
1 interacts with 1 qubit
1 interacts with 2 qubits
$\rho = (1 + \varepsilon Z_a)/|1|$
$\rightarrow \mathbb{1} + \varepsilon |4\rangle\langle 4|$

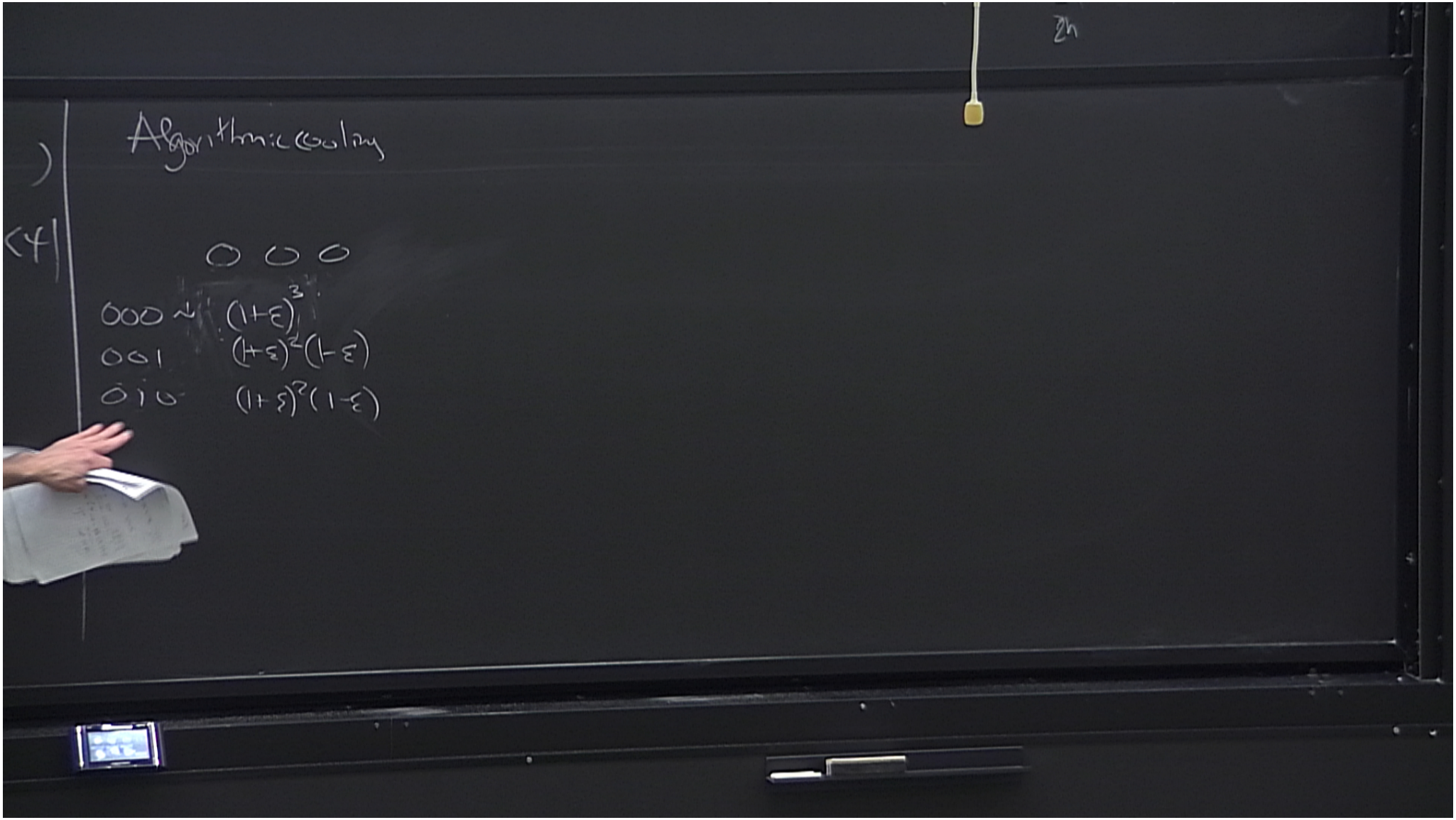

pseudo pure
1 qubit isolated
1 interacting with 1 qubit
1 interacting with
X|1111⟩
ρ = (1 + ε Z₀ |1⟩⟨1|)
→ 𝟙 + ε |4⟩⟨4|
Uput

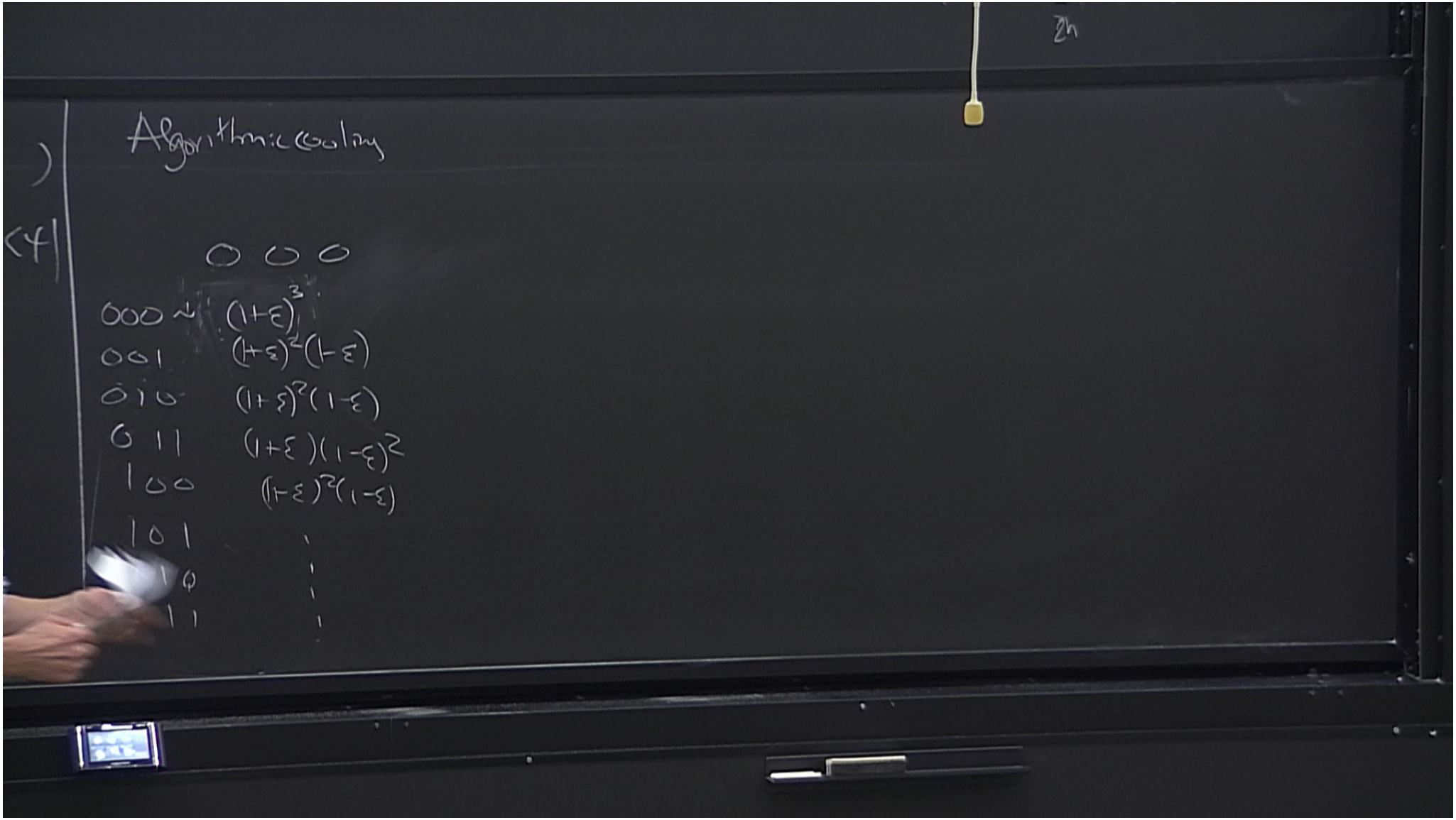

- 1 qubit gates
→ 2 qubit gates
J coupling.
$Z_1 Z_2$
pseudo pure
1 qubit rotated
1 interacts with 1 qubit
1 interacts with 2 qubits
$|1111\rangle$
$\rho = (1 + \varepsilon Z_a \mathbb{1} \mathbb{1} \mathbb{1})$
$\rightarrow \mathbb{1} + \varepsilon |4\rangle\langle 4|$
Uput

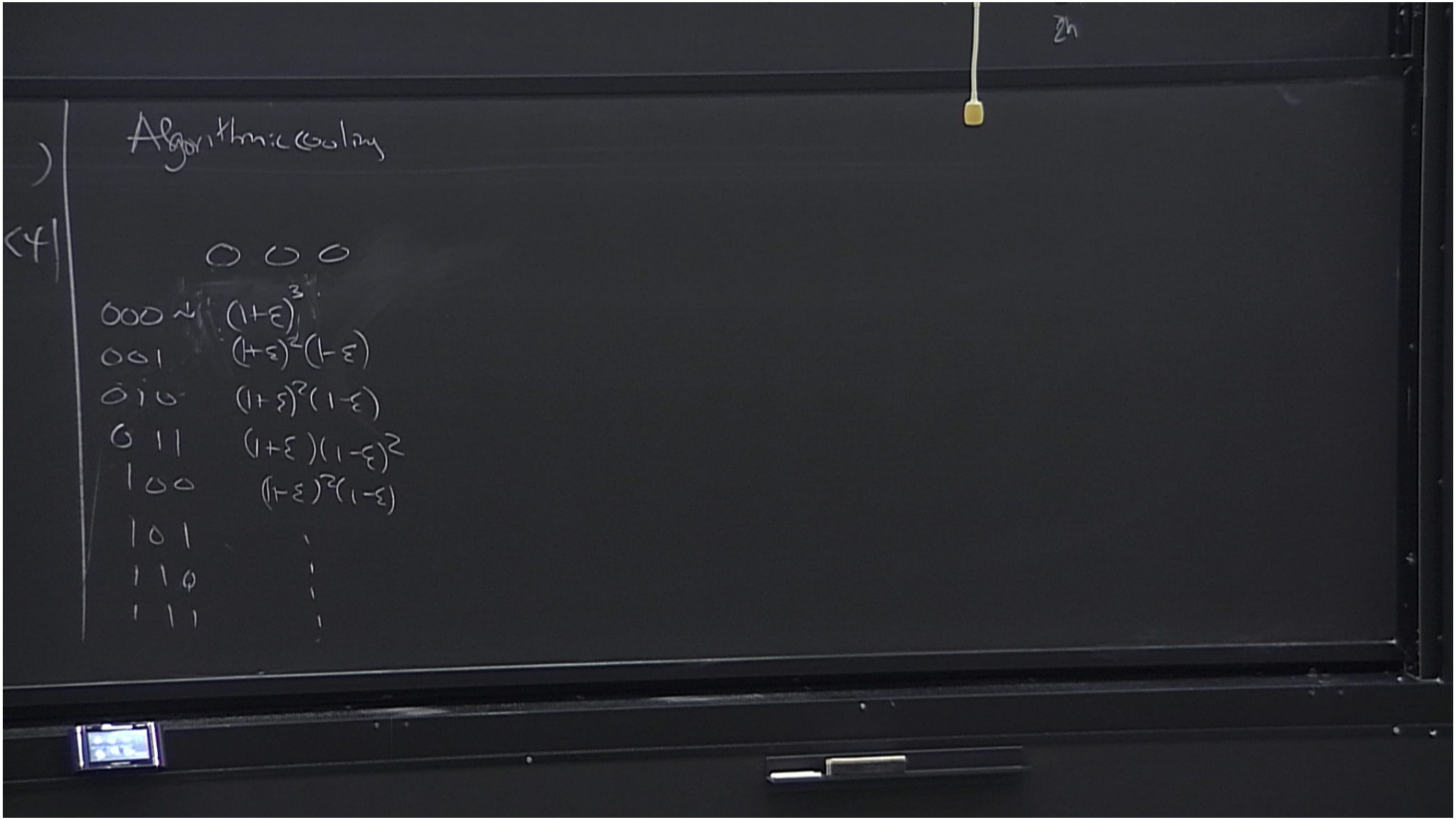

pseudo pure
1 qubit isolated
1 interacts with 1 qubit
1 interacts with 2 qubits
$\rho = (1 + \varepsilon Z_\alpha \otimes \mathbb{1} \otimes \cdots)$
$\rightarrow \mathbb{1} + \frac{\varepsilon}{2^n} |4\rangle\langle 4|$
Uput

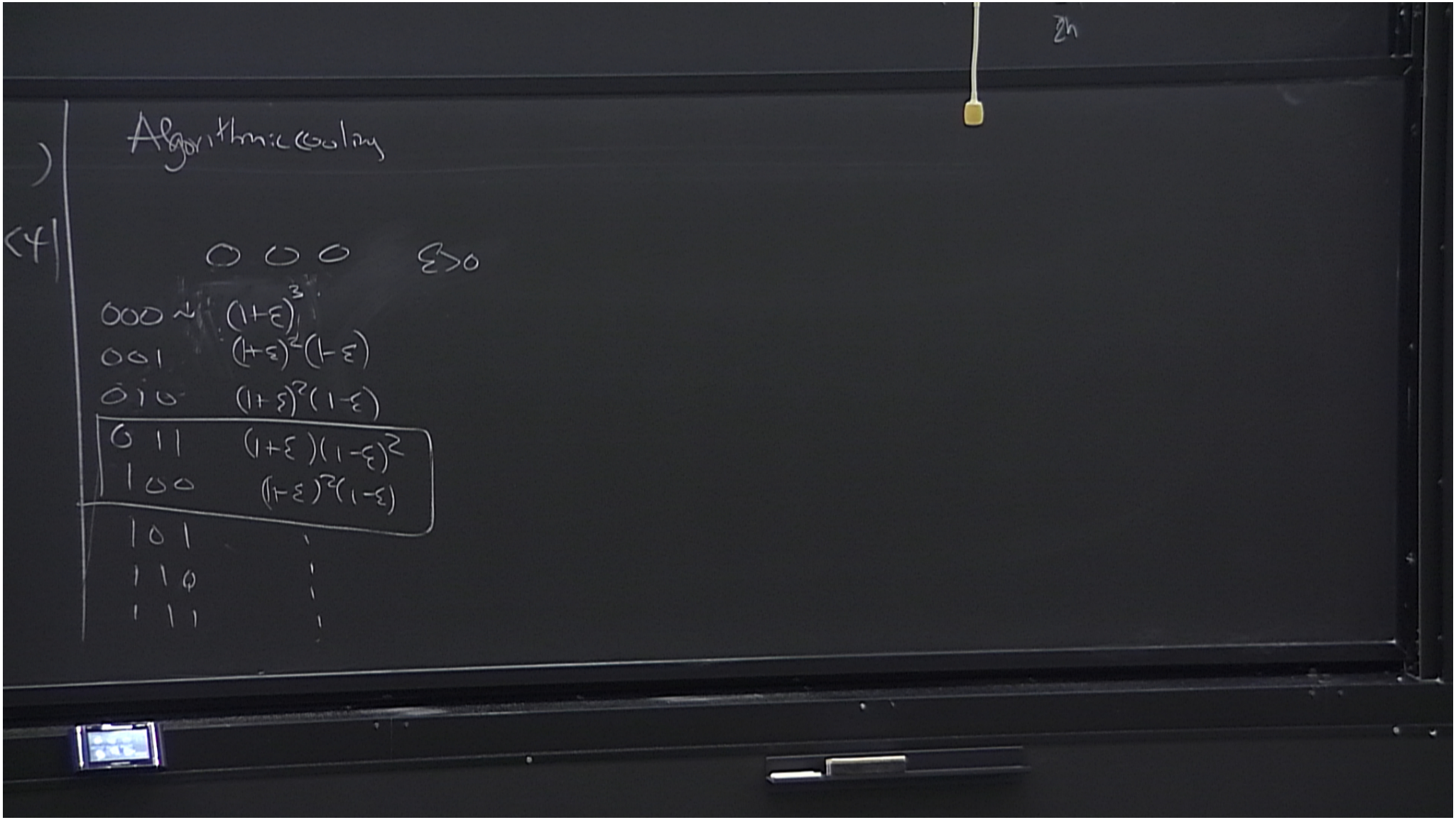

Algorithmic Cooling

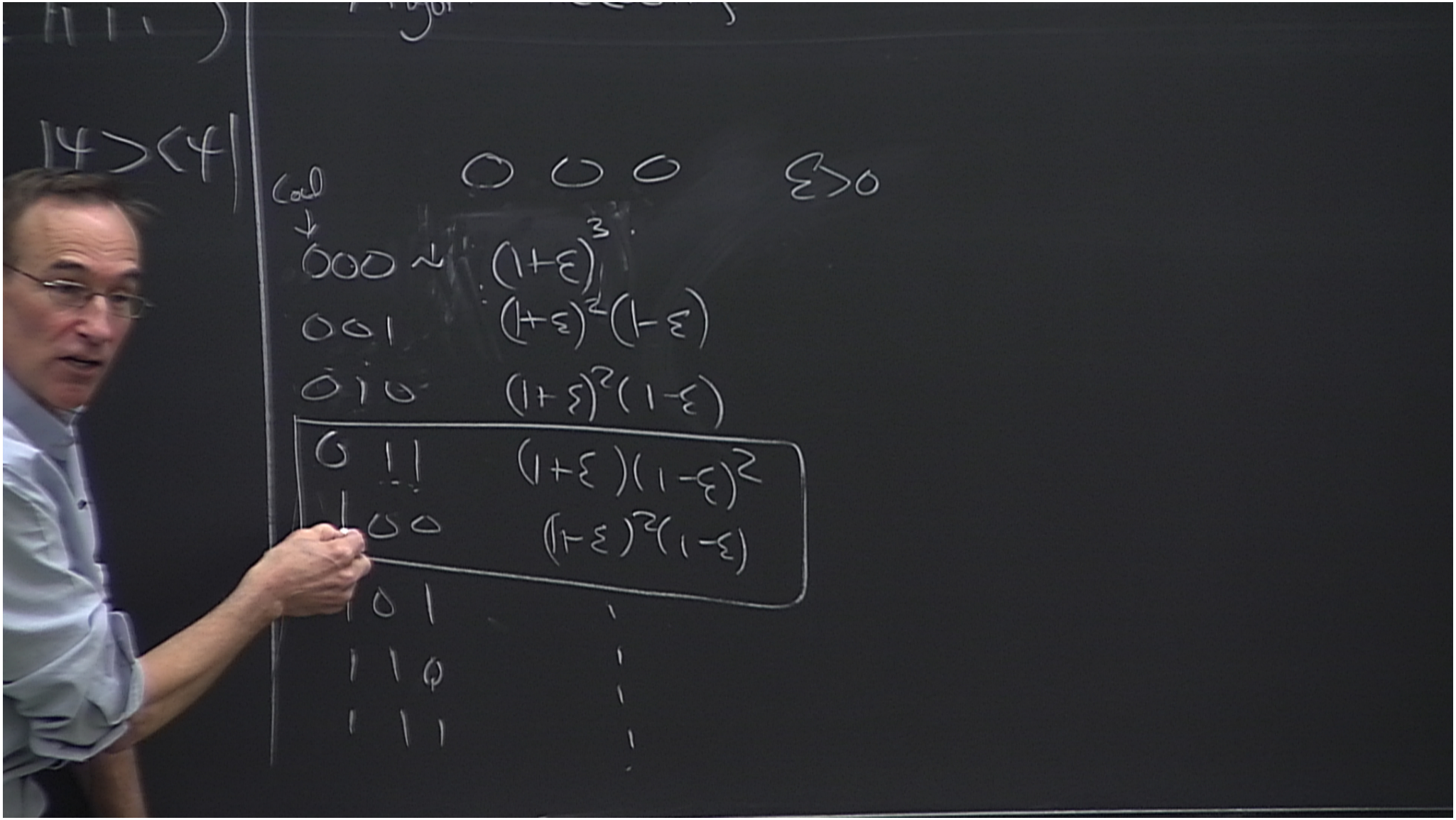

Algorithmic Cooling
000 ~ $(1+\varepsilon)^3$
001 $(1+\varepsilon)^2(1-\varepsilon)$

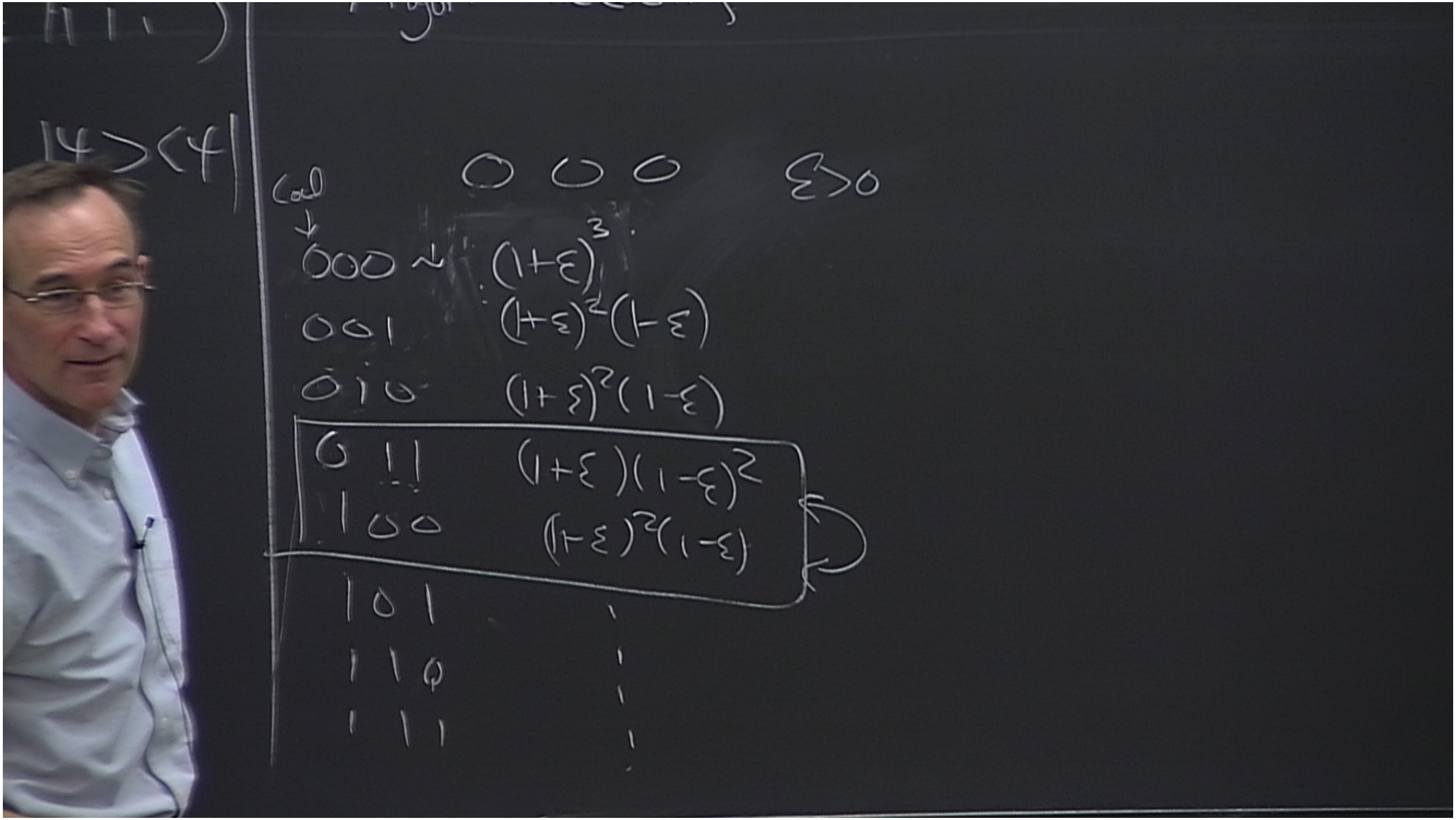

Algorithmic Cooling
000 ~ $(1+\varepsilon)^3$
001 $(1+\varepsilon)^2(1-\varepsilon)$
010 $(1+\varepsilon)^2(1-\varepsilon)$

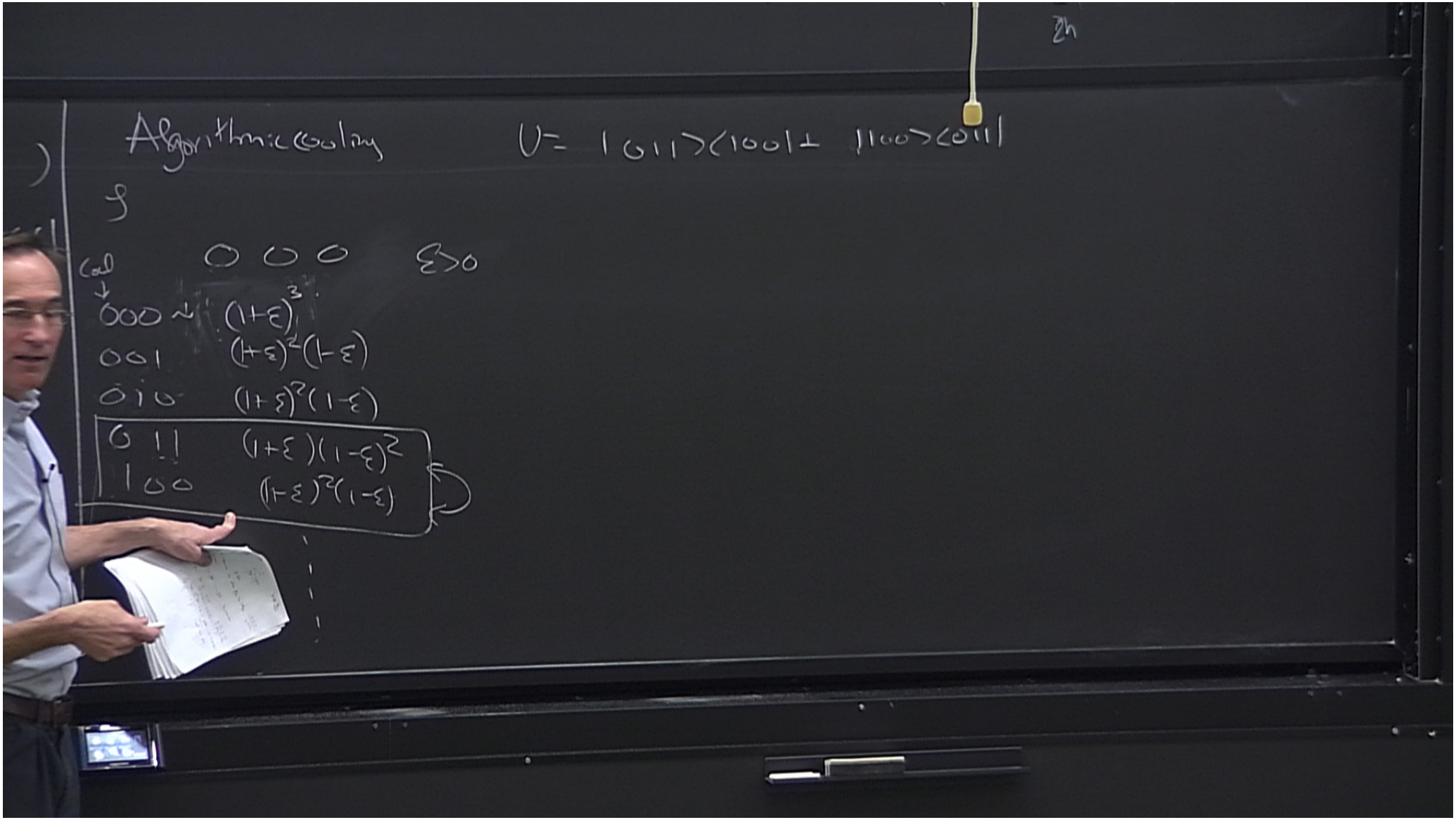

Algorithmic Cooling
000 ~ (1+ε)^3
001 (1+ε)^2(1-ε)
010 (1+ε)(1-ε)^2
011 (1+ε)(1-ε)^2
100 (1+ε)(1-ε)^2
101
110
111

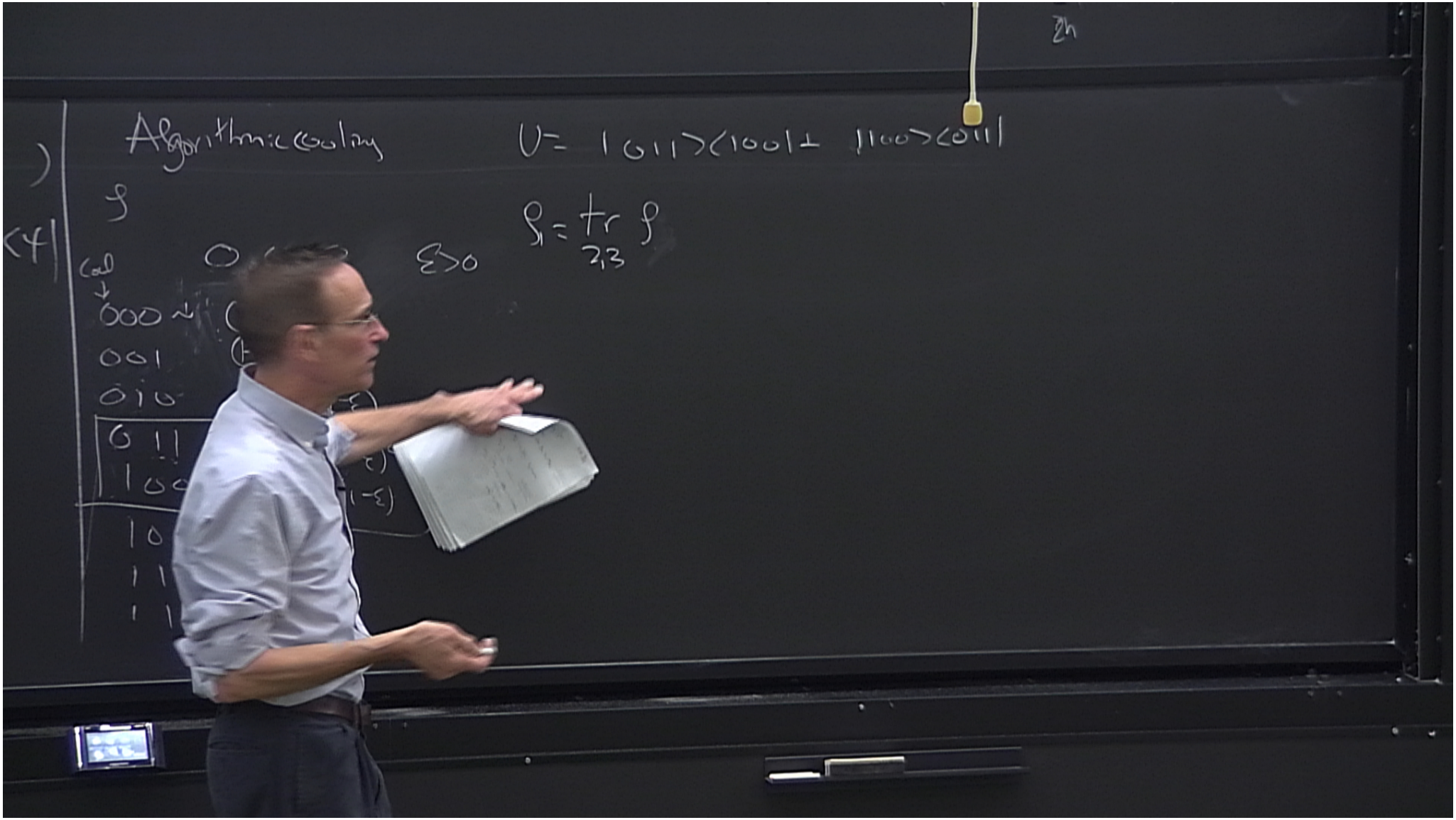

Algorithmic Cooling
000 ~ (1+ε)^3
001 (1-ε)^2(1+ε)
010 (1-ε)^2(1+ε)
011 2(1-ε)(1+ε)
100 (1-ε)^2(1+ε)

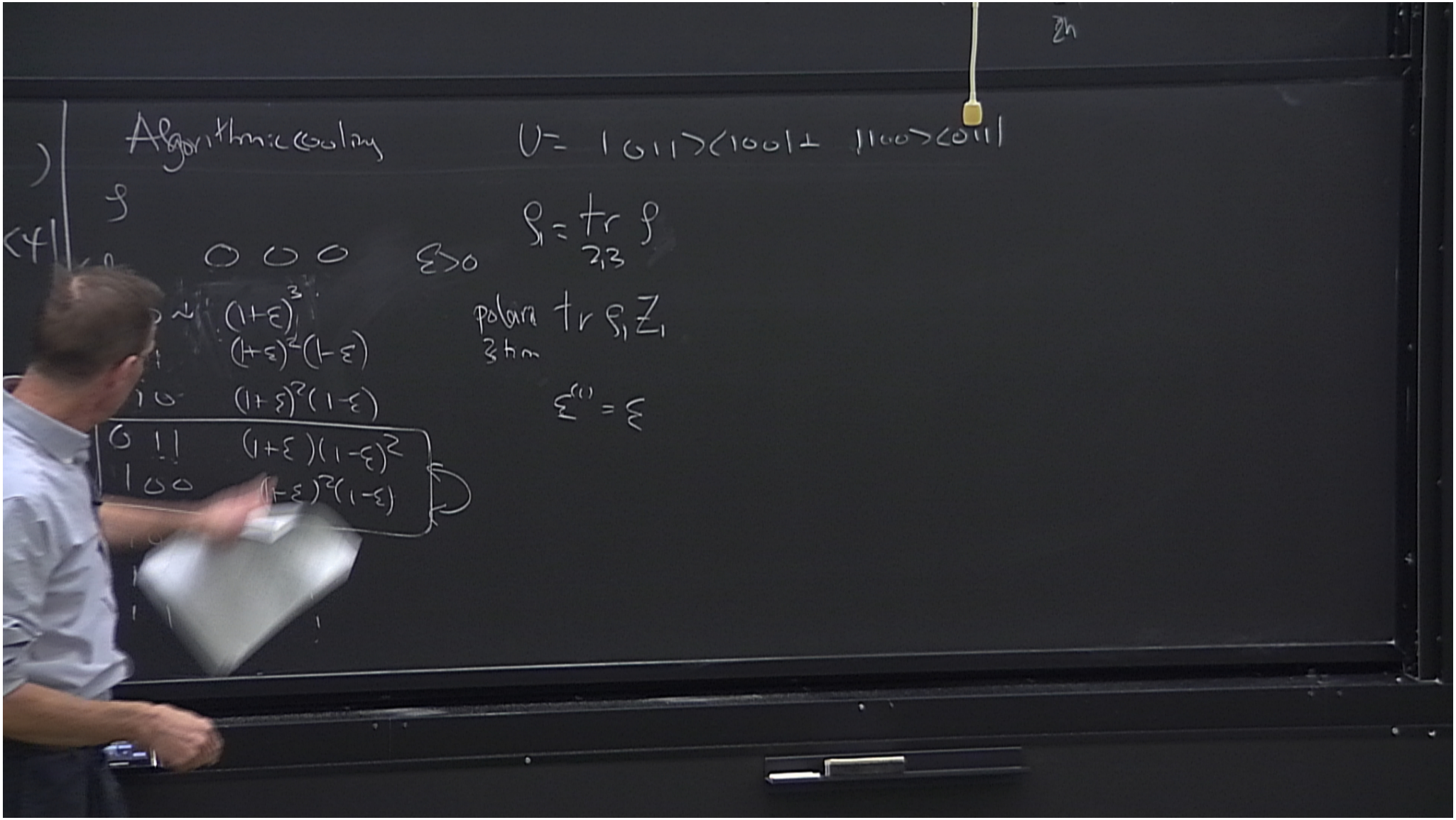

Algorithmic Cooling
000 ~ (1+ε)^3
100 (1-ε)^2(1+ε)
010 (1-ε)^2(1+ε)
011 (1-ε)(1+ε)^2
001 (1-ε)^2(1+ε)

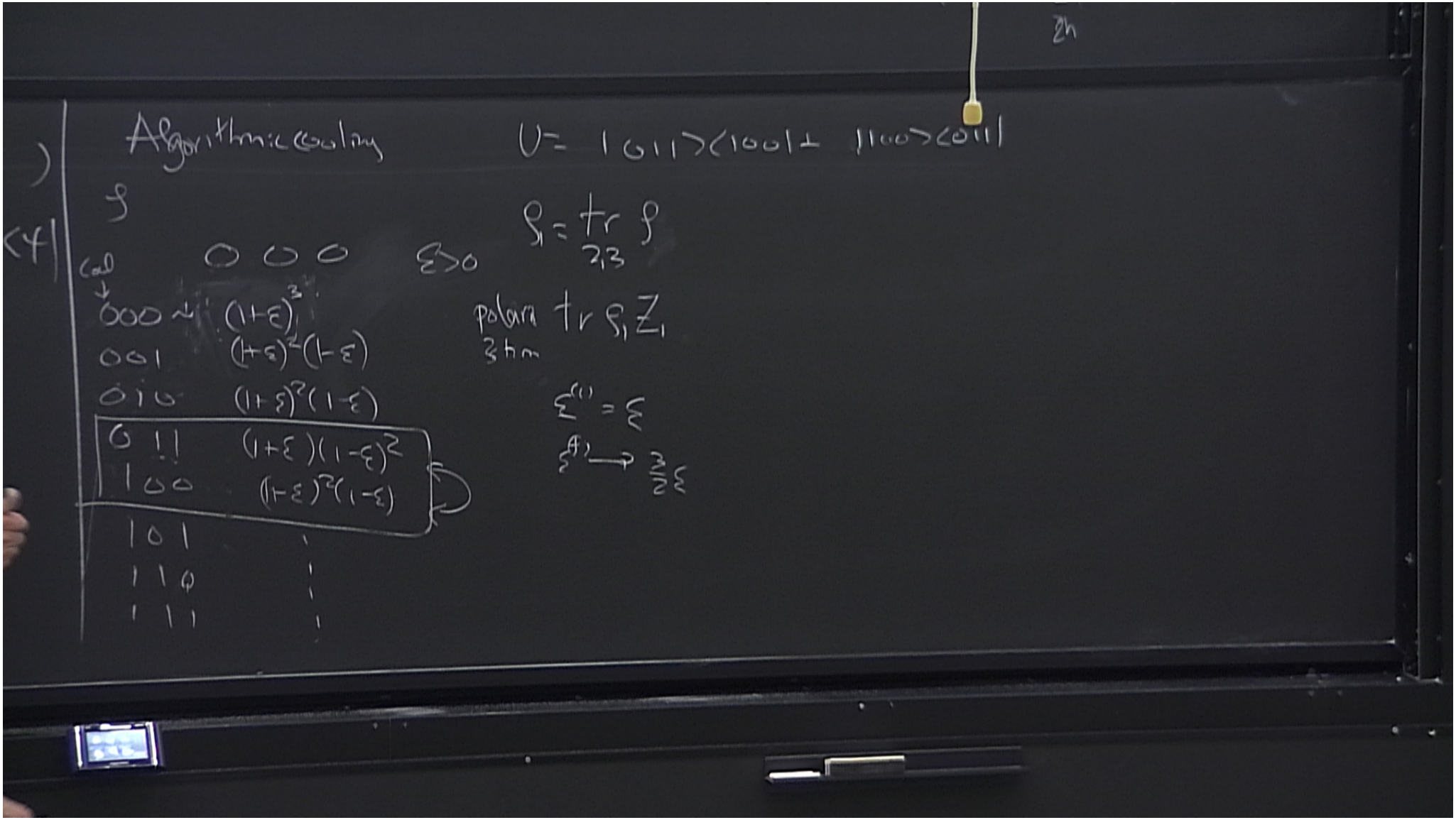

|4><4|
col
000 ~ $(1+\varepsilon)^3$
001 $(1-\varepsilon)^2(1+\varepsilon)$
010 $(1-\varepsilon)^2(1+\varepsilon)$
011 $\varepsilon(1-\varepsilon)(1+\varepsilon)$
100 $(1-\varepsilon)^2(1+\varepsilon)$
101
110
111
$0 < \varepsilon$

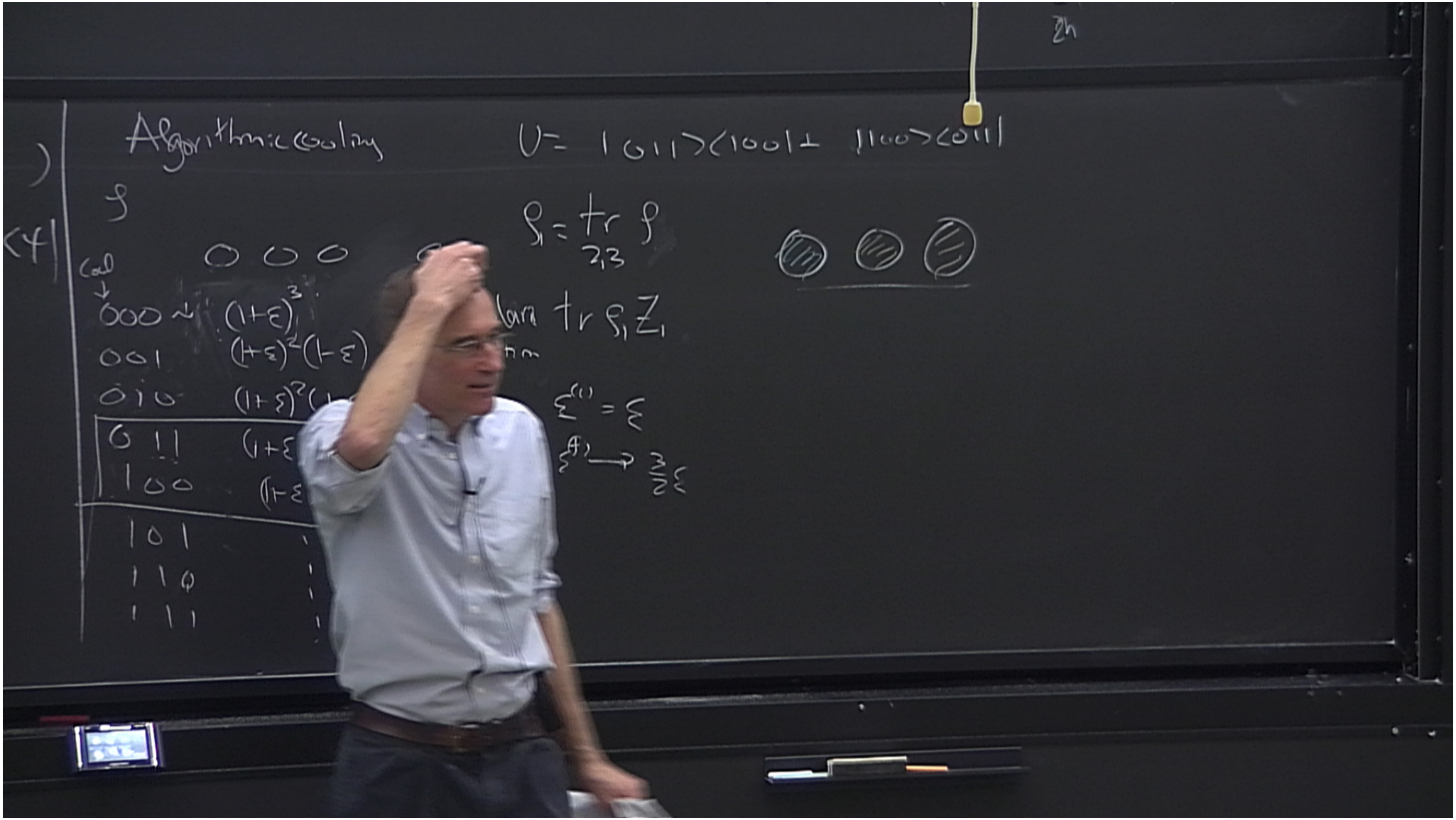

|4><4|
col
000 ~ (1+ε)^3
001 (1-ε)^2(1+ε)
010 (1+ε)^2(1-ε)
011 (1-ε)^2(1+ε)
100 (1+ε)^2(1-ε)
101
110
111
0<ε

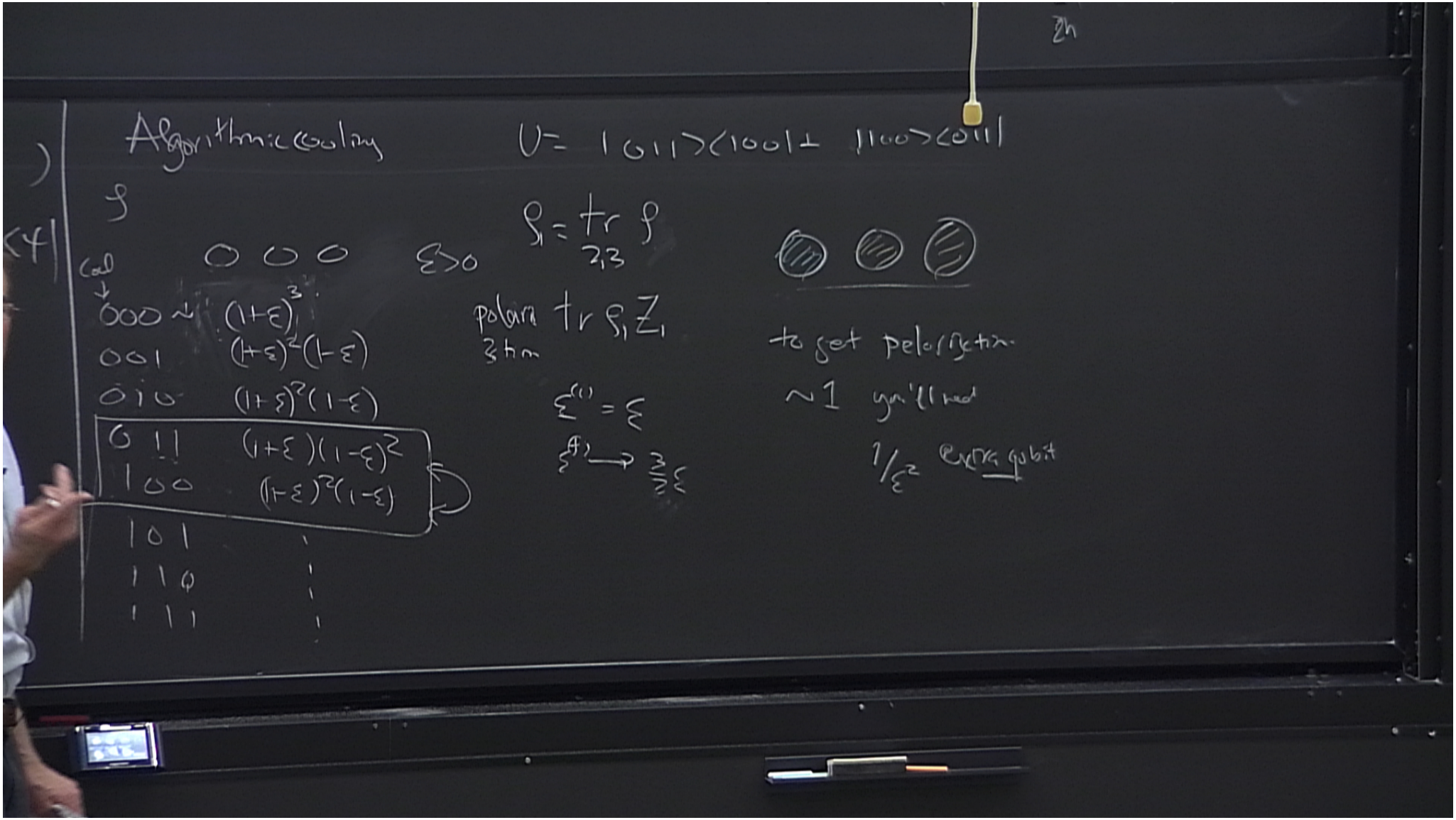

Algorithmic cooling
$U = |011\rangle\langle 100| + |100\rangle\langle 011|$
ε
$000 \sim (1+\varepsilon)^3$
$100 \quad (1-\varepsilon)(1+\varepsilon)^2$
$010 \quad (1-\varepsilon)^2(1+\varepsilon)$
$001 \quad (1-\varepsilon)^2(1+\varepsilon)$
$111 \quad (1-\varepsilon)(1+\varepsilon)^2$

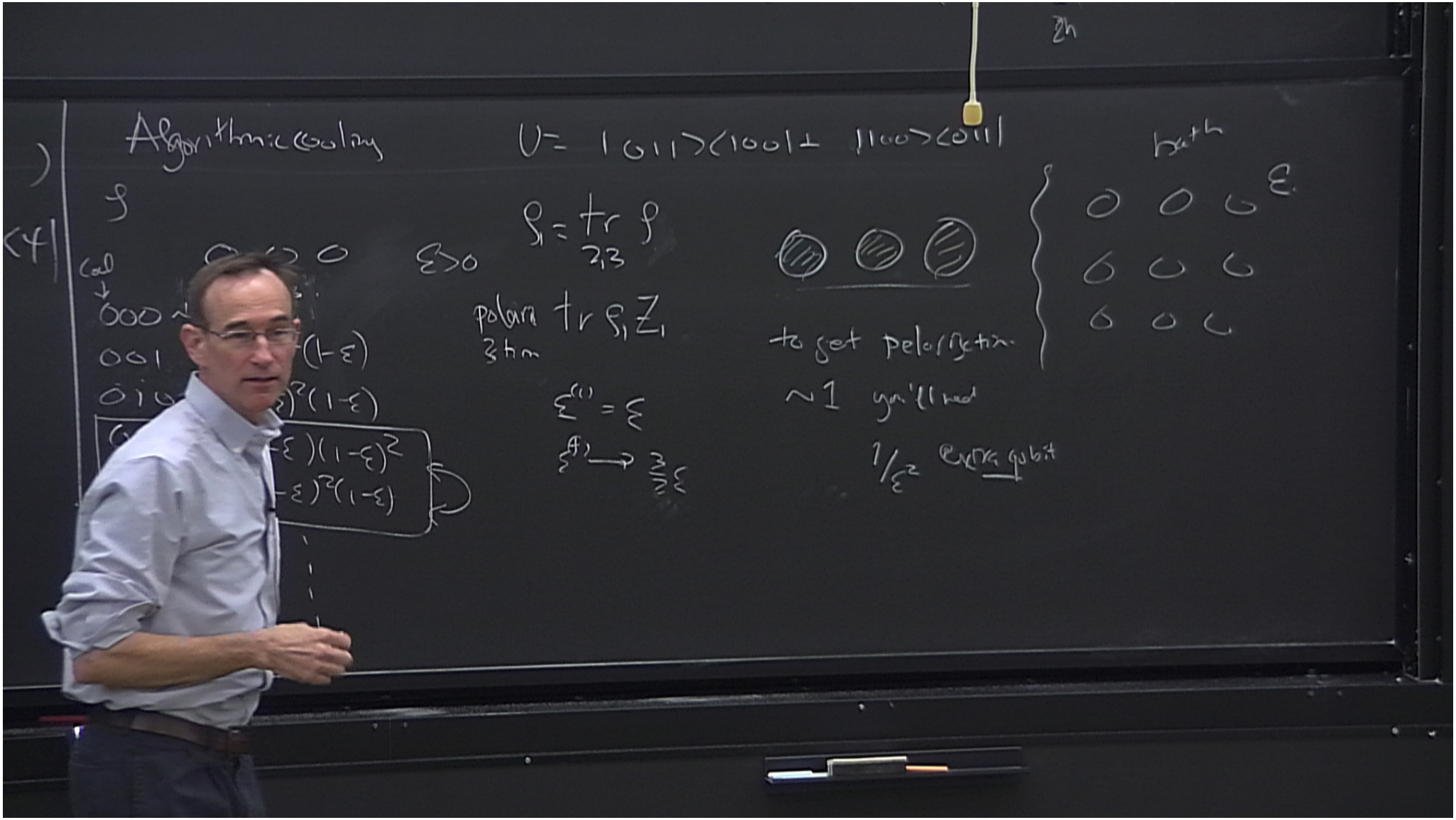

Algorithmic cooling
$U = |011\rangle\langle 100| + |100\rangle\langle 011|$
ρ
$\rho_1 = tr_{2,3}\,\rho$
$\varepsilon > 0$
000
001
010
011
100
10
11
1 1

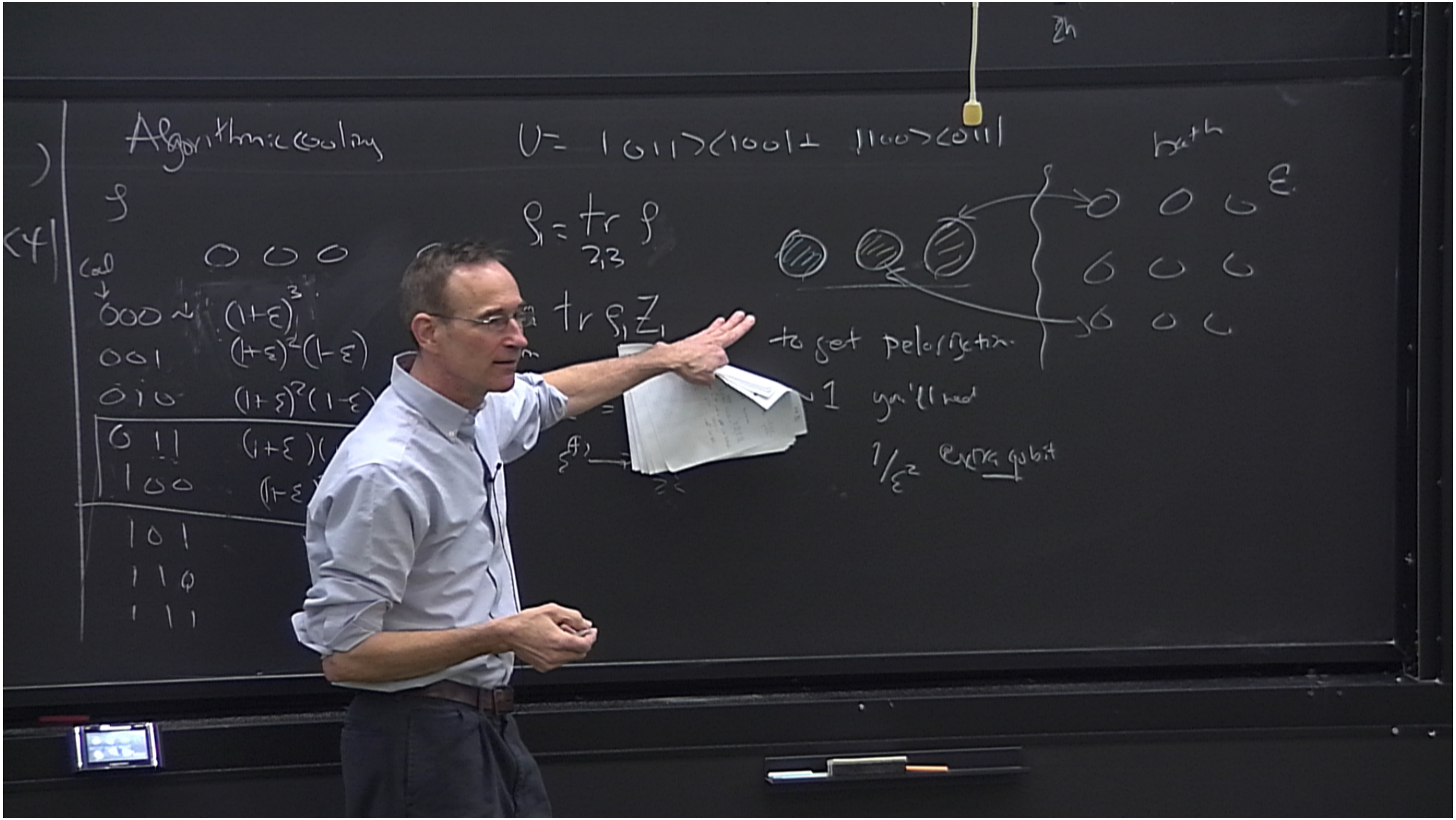

Algorithmic cooling
$U = |01\rangle\langle 10| + |10\rangle\langle 01|$
ρ
$\rho_1 = \mathrm{tr}_{2,3}\,\rho$
$\varepsilon > 0$
$(1+\varepsilon)^3$
$(1-\varepsilon)^2(1+\varepsilon)$
$(1-\varepsilon)^2(1+\varepsilon)$
$(1-\varepsilon)(1+\varepsilon)^2$
$(1-\varepsilon)^2(1+\varepsilon)$
polarization
$\mathrm{tr}\,\rho_1 Z_1$
$\varepsilon' > \varepsilon$

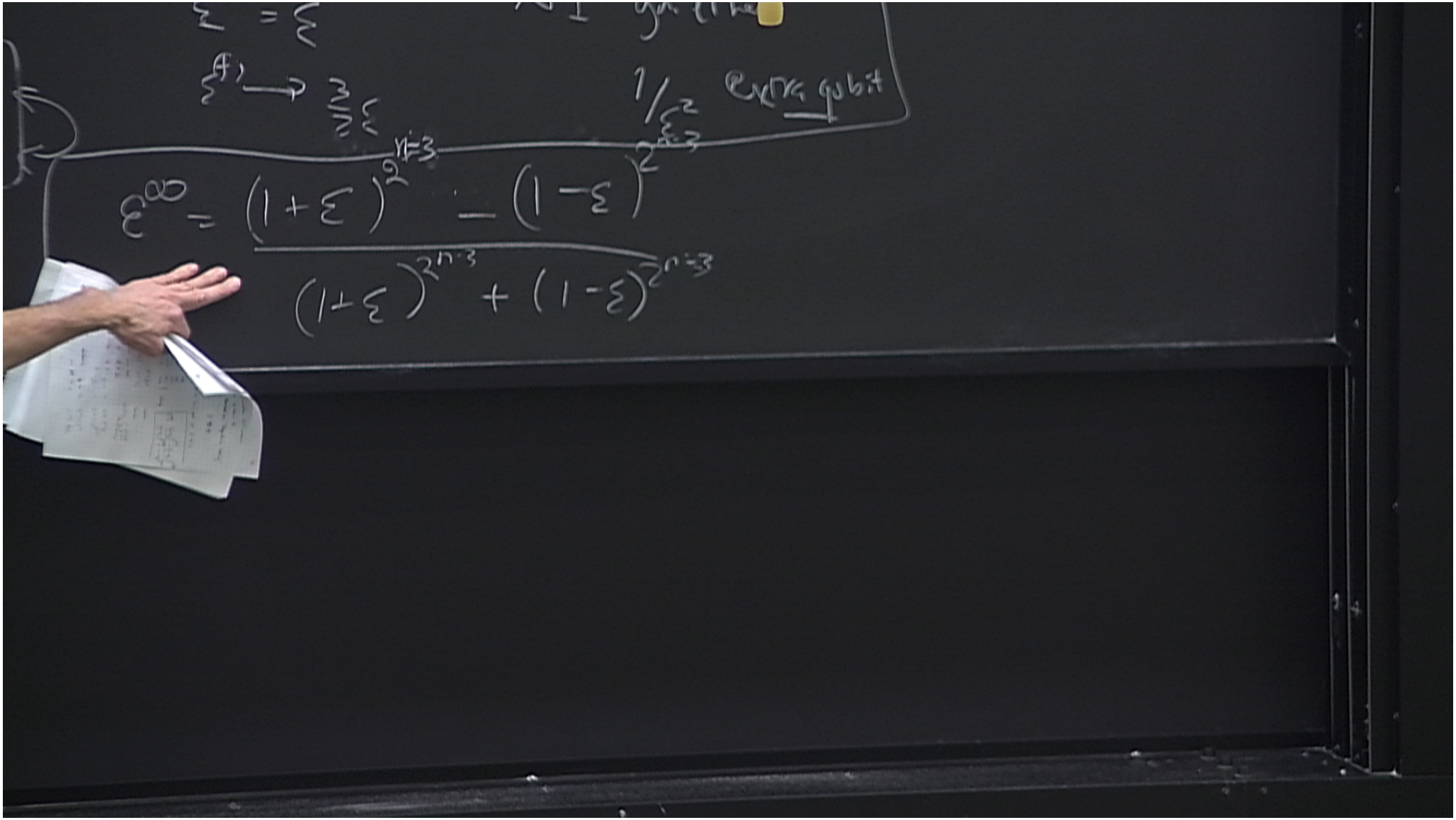

Algorithmic cooling
$U = |01\rangle\langle 100| + |100\rangle\langle 011|$
ρ
$\rho_1 = \mathrm{tr}_{2,3}\,\rho$
cool
000
001
010
011
100
101
110
111
$\varepsilon > 0$
$(1+\varepsilon)^3$
$(1-\varepsilon)^2(1+\varepsilon)$
$(1-\varepsilon)^2(1+\varepsilon)$
$\varepsilon^2(1-\varepsilon)(1+\varepsilon)$
$(1-\varepsilon)^2(1+\varepsilon)$
polarization
$\mathrm{tr}\,\rho_1 Z_1$
$\varepsilon' = \frac{3}{2}\varepsilon$

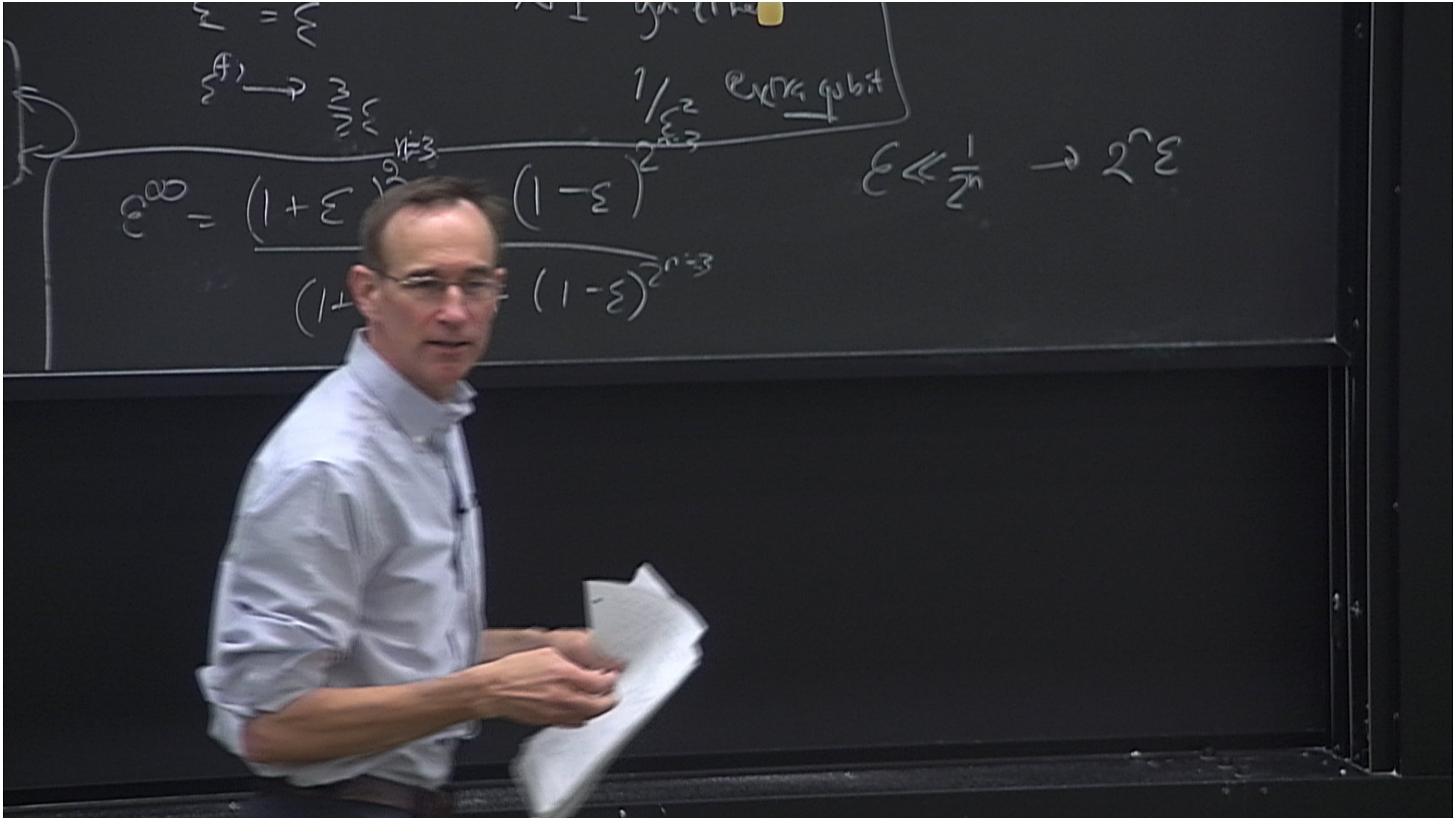

Algorithmic cooling
$U = |011\rangle\langle 100| + |100\rangle\langle 011|$
$\rho_1 = \mathrm{tr}_{2,3}\,\rho$
cool
000
001
010
011
100
101
110
111
$(1+\varepsilon)^3$
$(1+\varepsilon)^2(1-\varepsilon)$
$\mathrm{tr}\,\rho_1 Z_1$
$\varepsilon^{(1)} = \varepsilon$
$\varepsilon^{(k)} \to \frac{3}{2}\varepsilon$

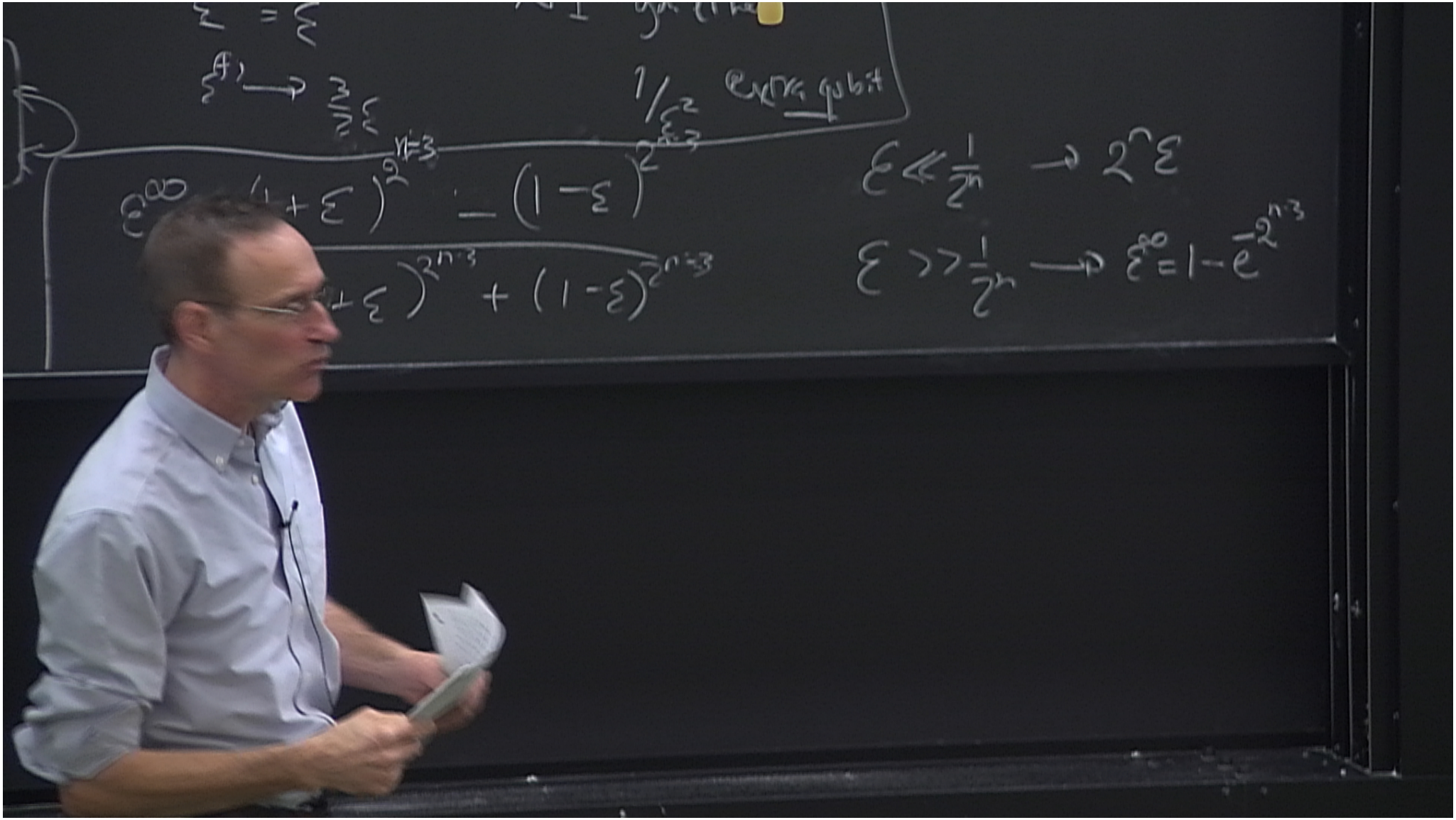

Algorithmic cooling
$U = |011\rangle\langle 100| + |100\rangle\langle 011|$
ρ
$\rho_1 = \mathrm{tr}_{2,3}\,\rho$
cool
000 ~ $(1+\varepsilon)^3$
001 $(1-\varepsilon)^2(1+\varepsilon)$
010 $(1-\varepsilon)^2(1+\varepsilon)$
011 $(1-\varepsilon)(1+\varepsilon)^2$
100 $(1-\varepsilon)^2(1+\varepsilon)$
101
110
111
$\varepsilon > 0$
polarization
$\mathrm{tr}\,\rho_1 Z_1$
$\varepsilon' = \varepsilon$
$\varepsilon \to \varepsilon'$
to get polarization
~1
$1/\varepsilon^2$
extra qubit

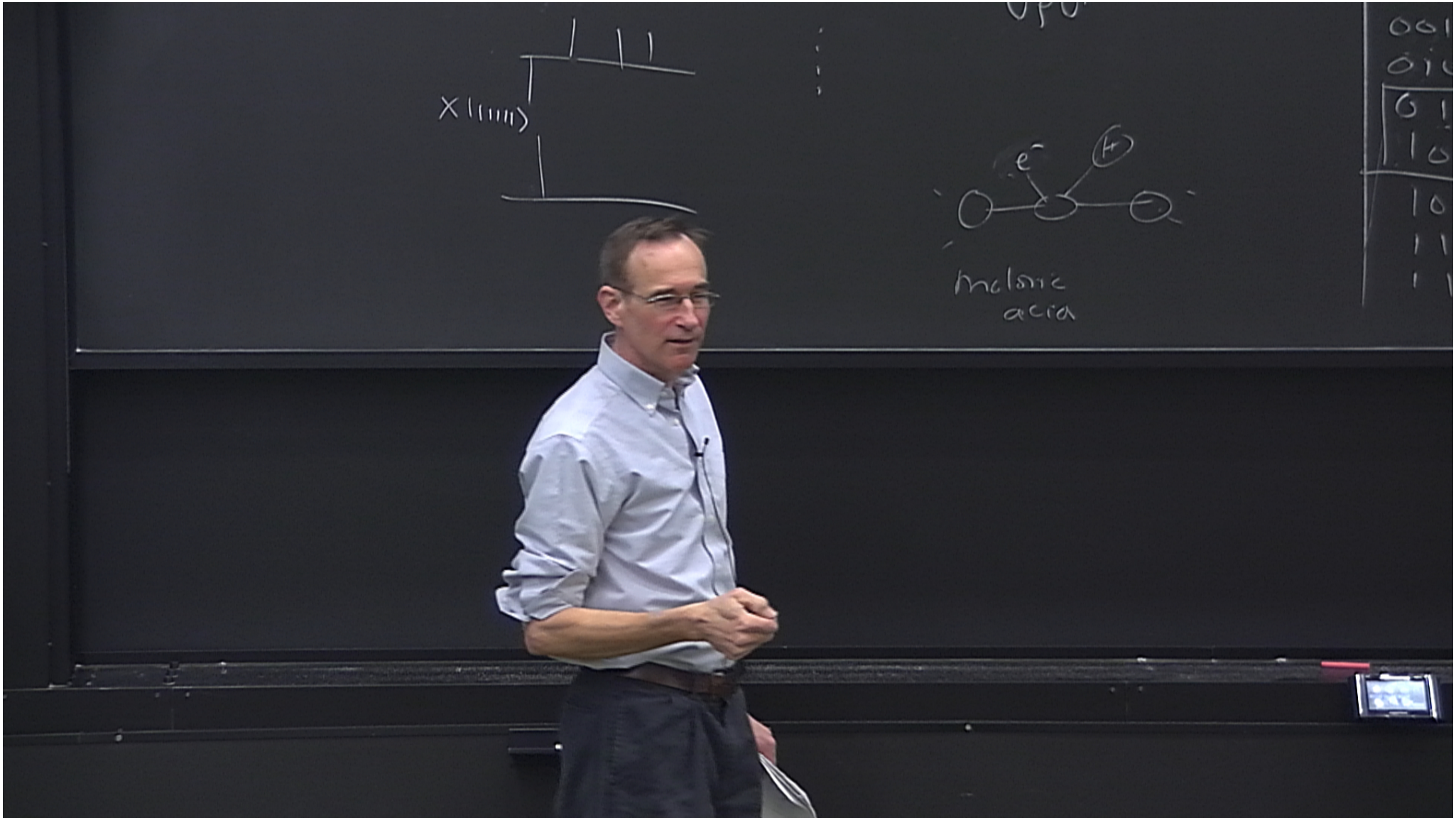

Algorithmic cooling
$U = |011\rangle\langle 100| + |100\rangle\langle 011|$
bath
$\rho_1 = \mathrm{tr}_{2,3}\,\rho$
$\varepsilon > 0$
polarization
$\mathrm{tr}\,\rho_1 Z_1$
to get polarization
~ 1 qubit
$1/\varepsilon^2$ extra qubit
$\varepsilon^{(1)} = \varepsilon$
$\varepsilon' \to \frac{3}{2}\varepsilon$

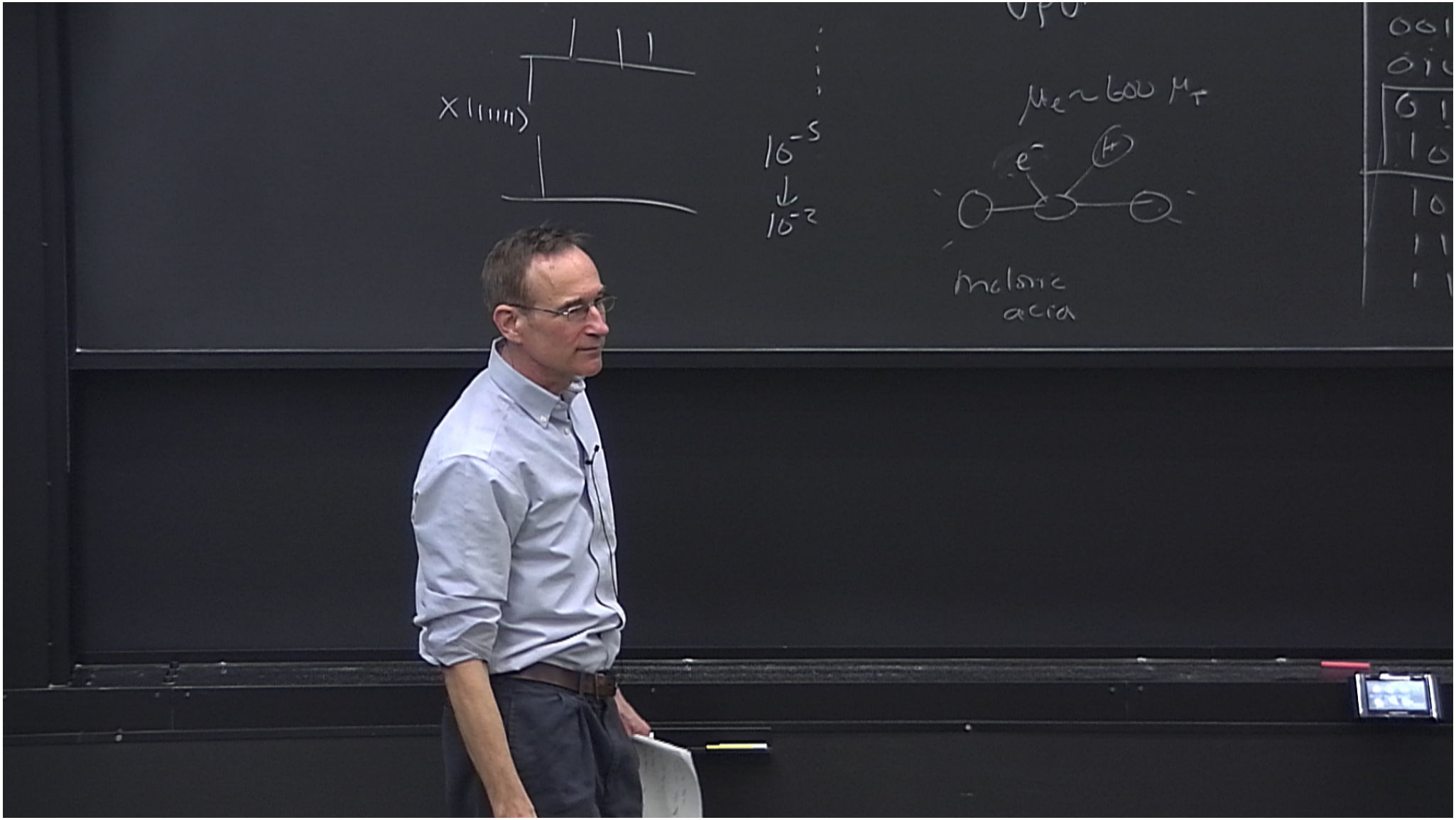

Algorithmic cooling
$U = |011\rangle\langle 100| + |100\rangle\langle 011|$
$\rho_1 = tr_{2,3}\,\rho$
$tr\,\rho_1 Z_1$
to get polarization
bath
cool
000 ~ $(1+\varepsilon)^3$
001 $(1+\varepsilon)^2(1-\varepsilon)$
010 $(1+\varepsilon)^2(1-\varepsilon)$
011
100
101
110
111
~1 qubit
$1/\varepsilon^2$ extra qubit

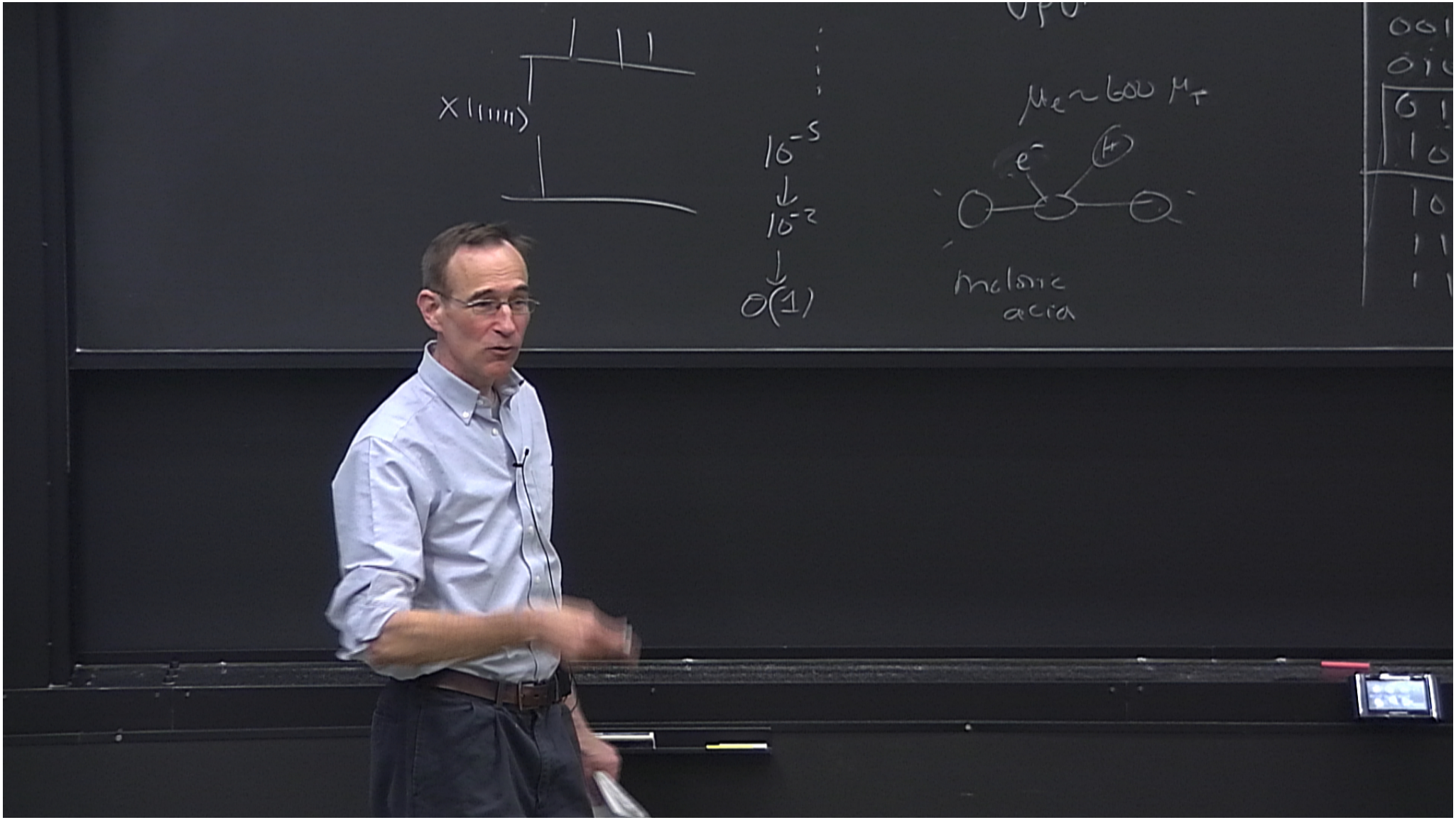

Extra qubit

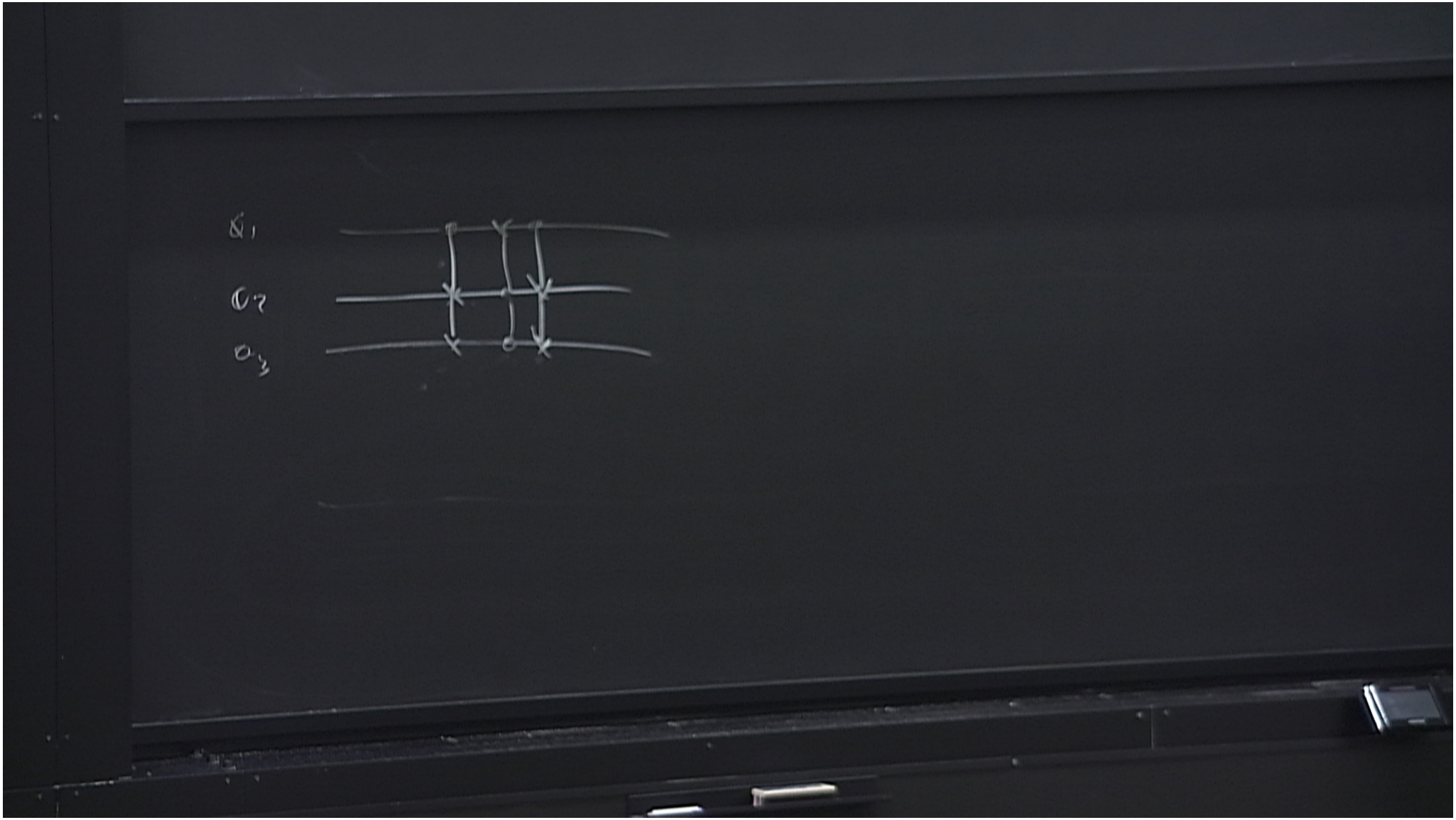

extra qubit
$\varepsilon \ll \frac{1}{2^n} \rightarrow 2^n\varepsilon$

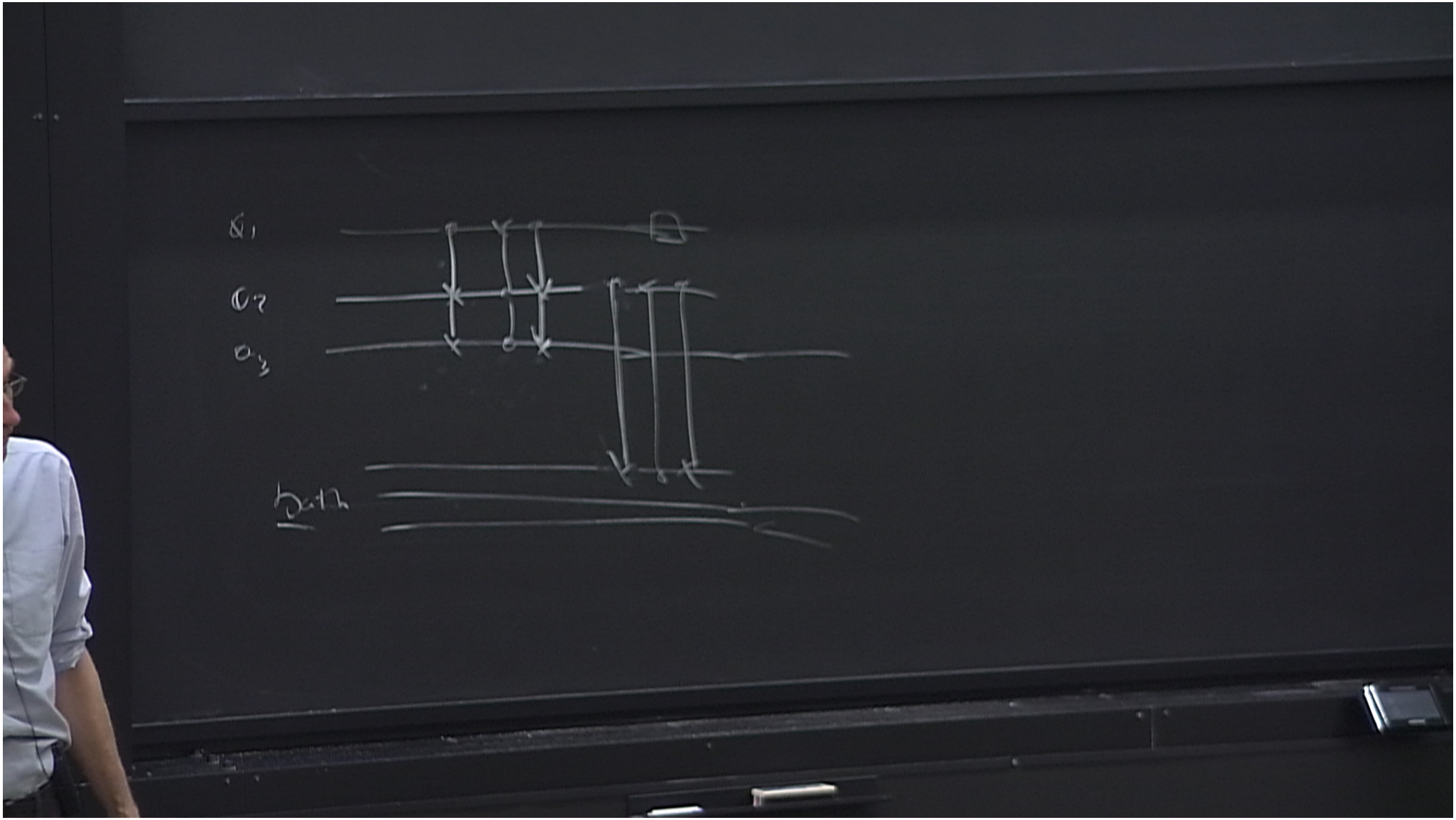

extra qubit
$\varepsilon \ll \frac{1}{2^n} \rightarrow 2^n\varepsilon$
$\varepsilon >> \frac{1}{2^n} \rightarrow \varepsilon^{\infty} = 1 - e^{-2^{n-3}}$

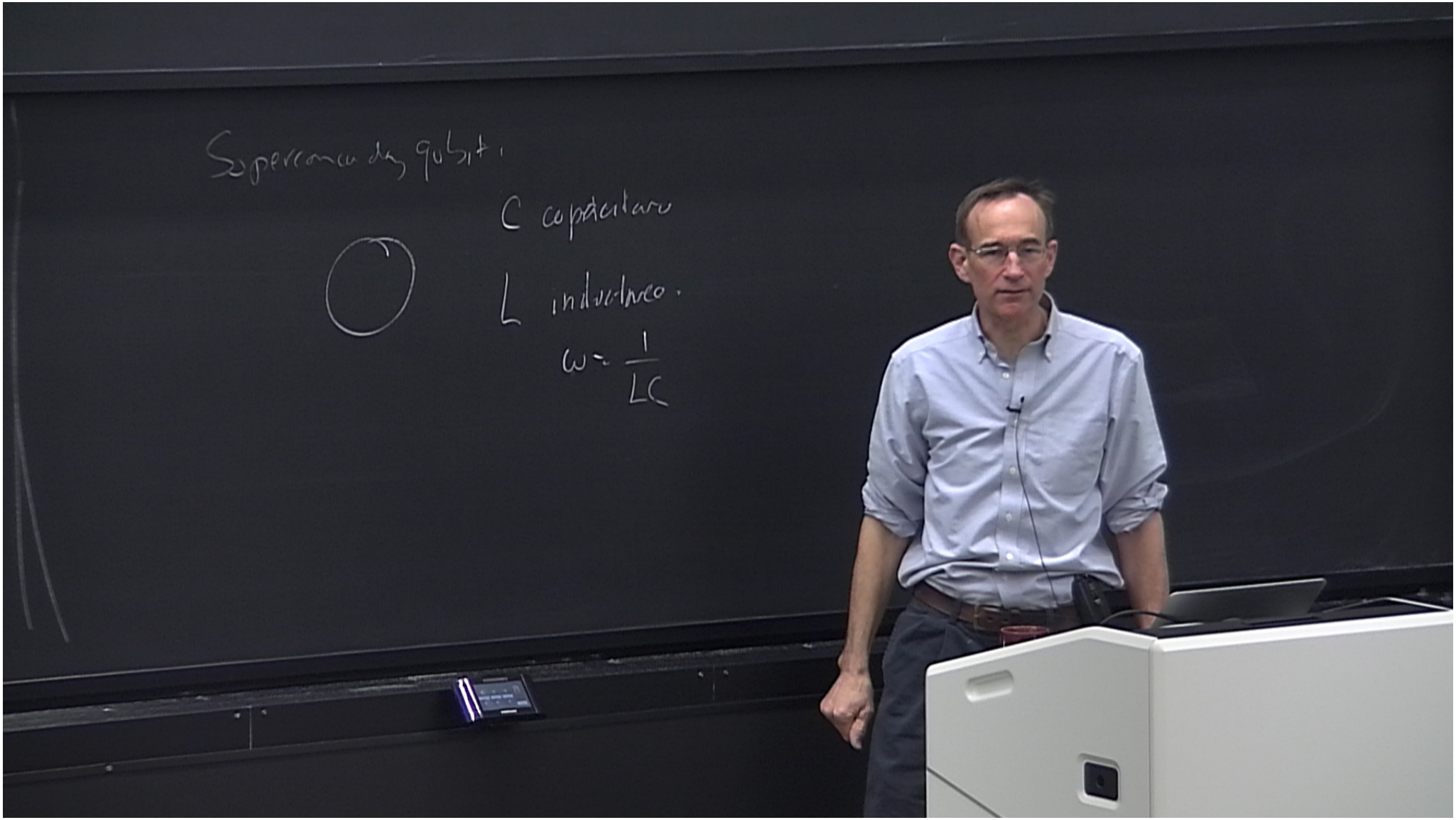

malonic
acid

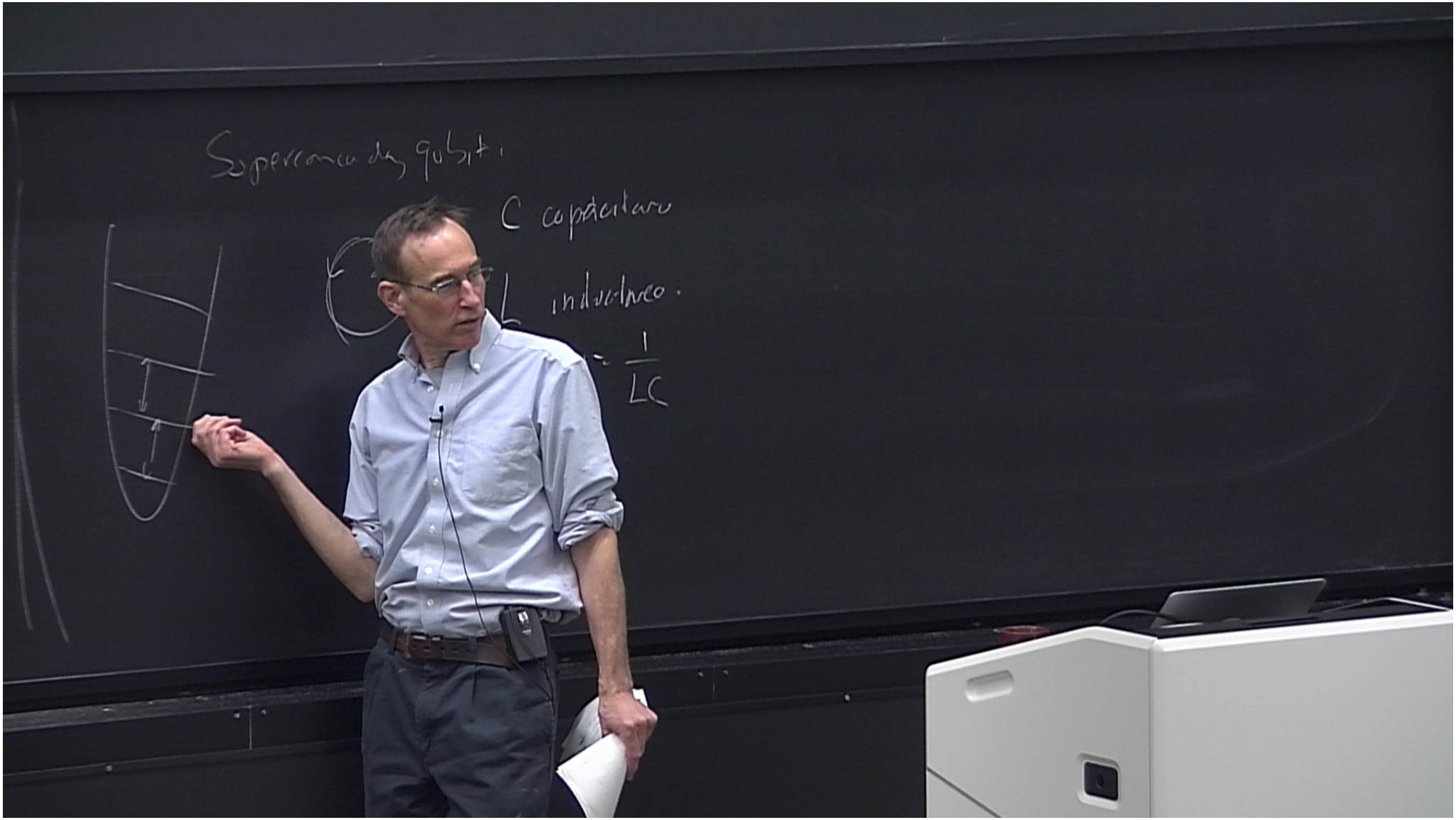

X (111)
10^{-5}
10^{-2}
$M_e \sim 600\ M_+$
e^-
H+
malonic
acid

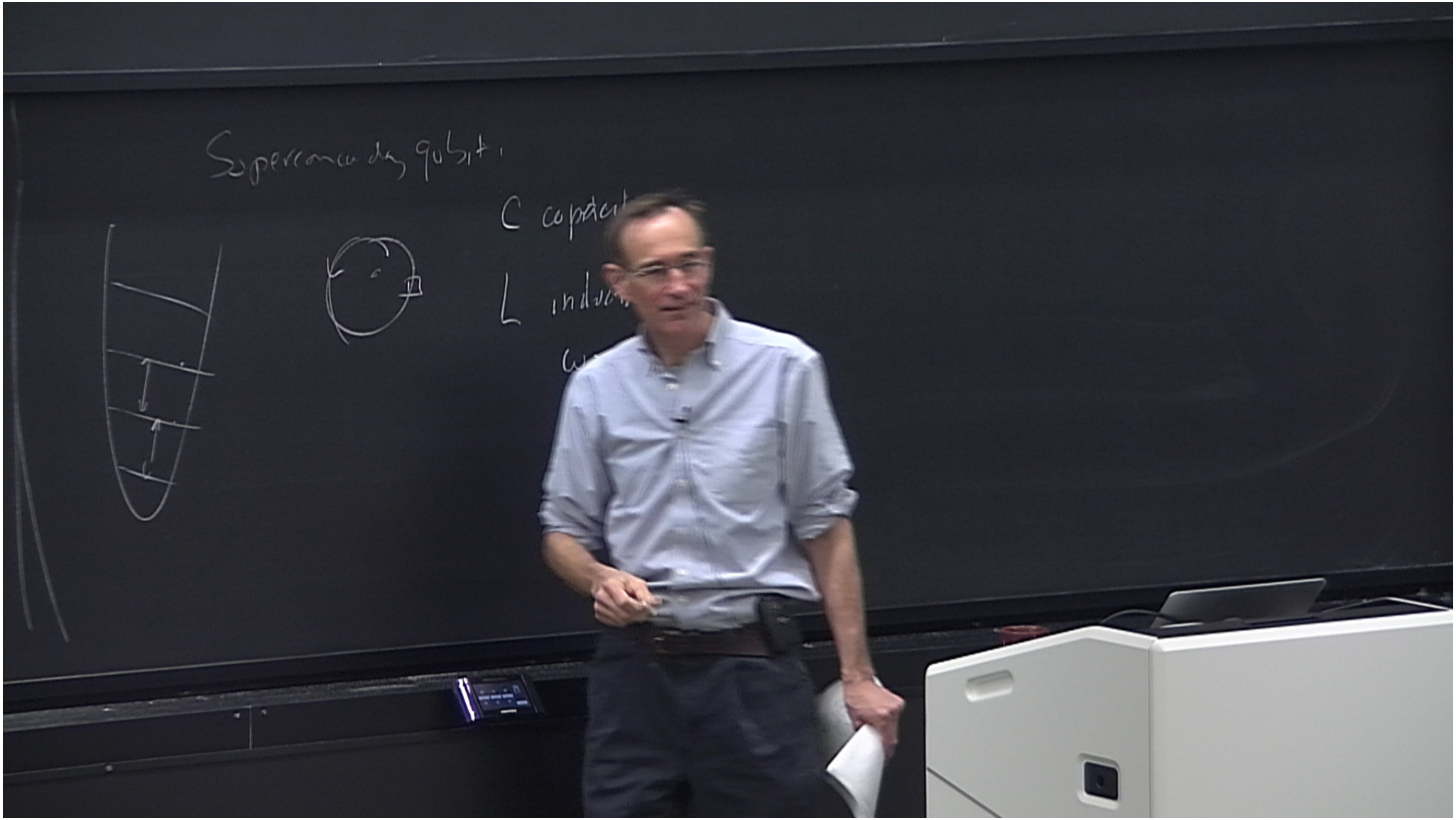

10^{-5}
10^{-2}
$O(1)$
$M_e \sim 600\, M_+$
malonic
acid

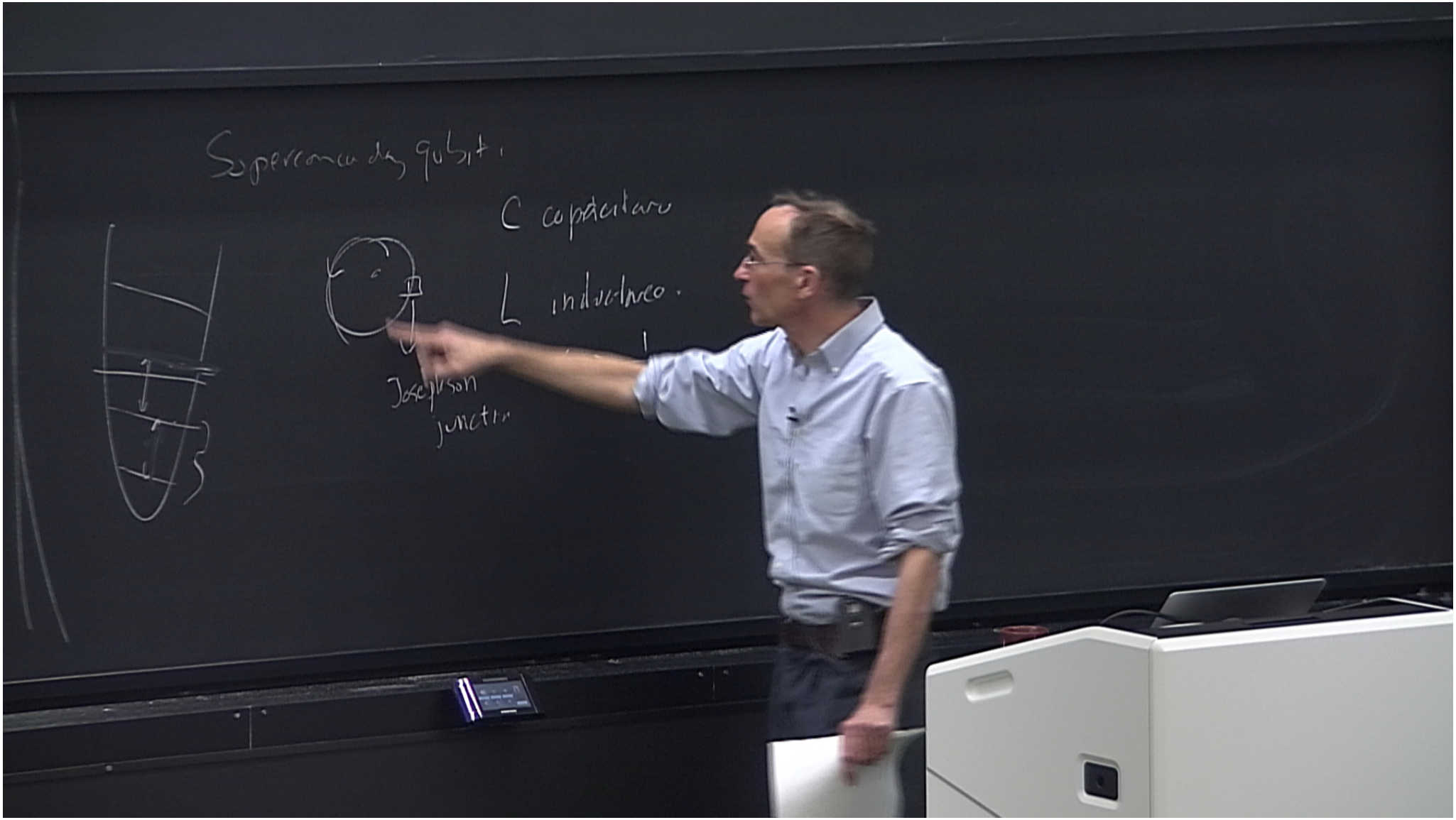

α_1
α_2
α_3

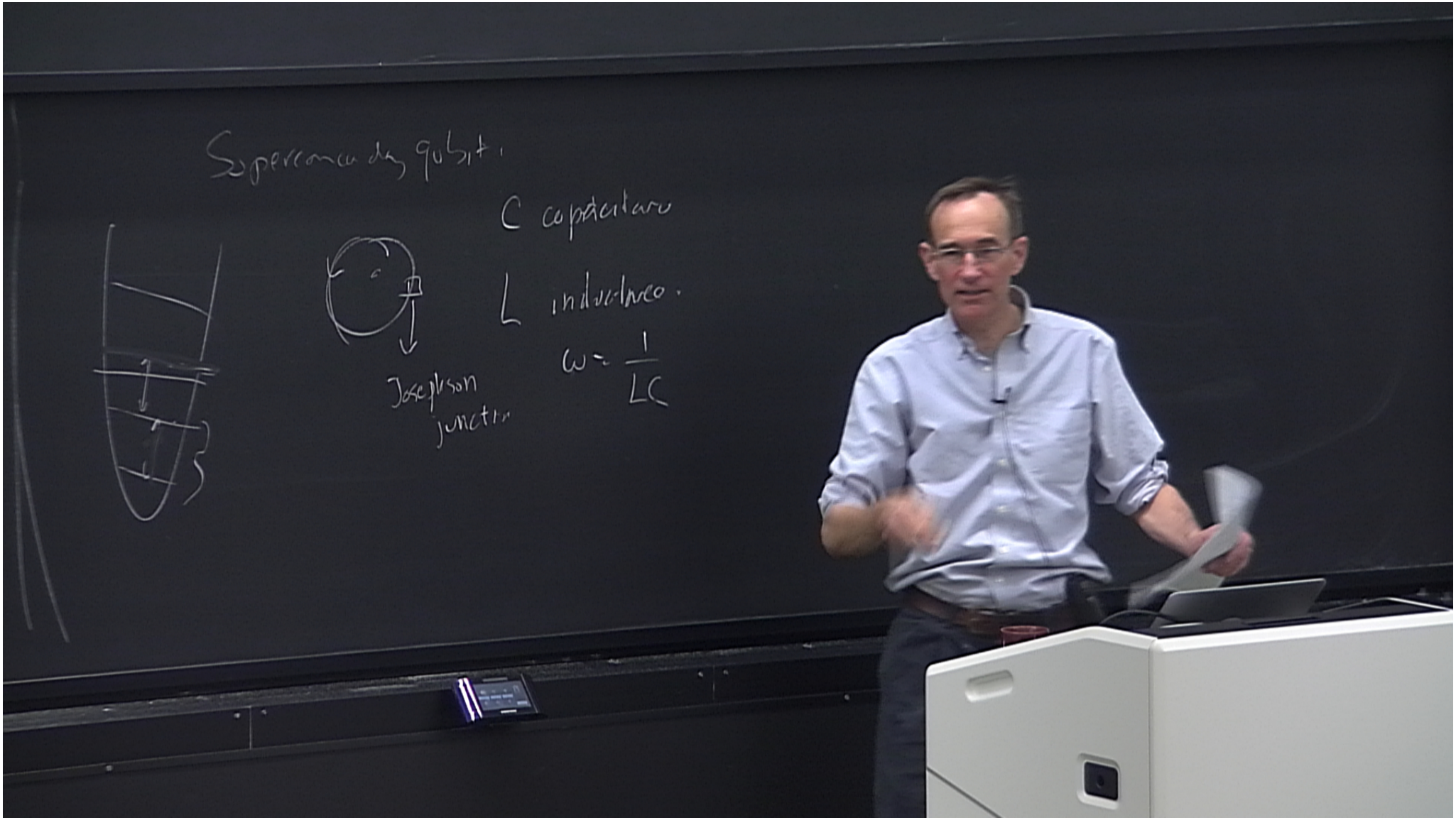

bath

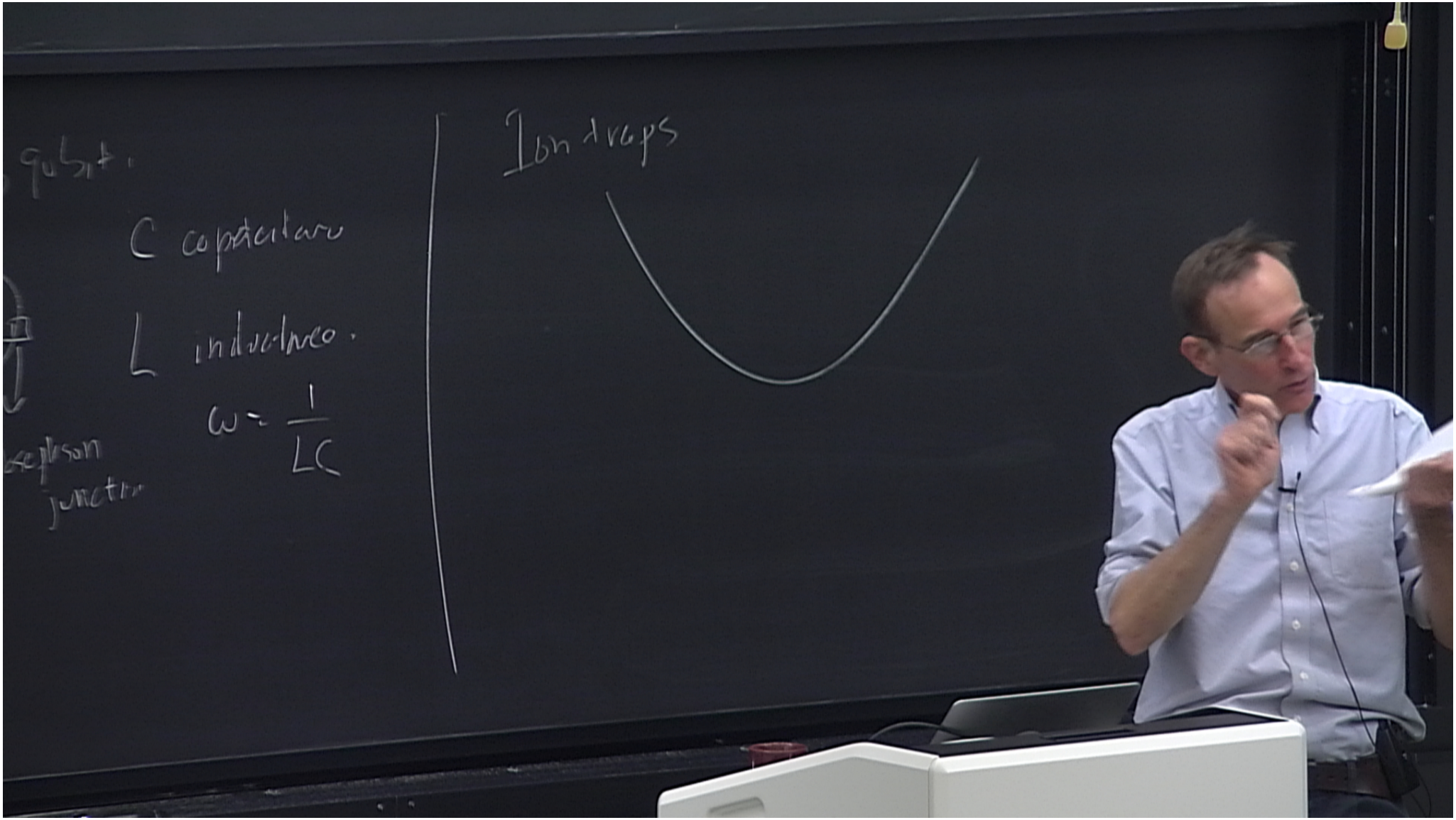

Superconducting qubit.
C capacitance
L inductance.
$\omega = \frac{1}{LC}$

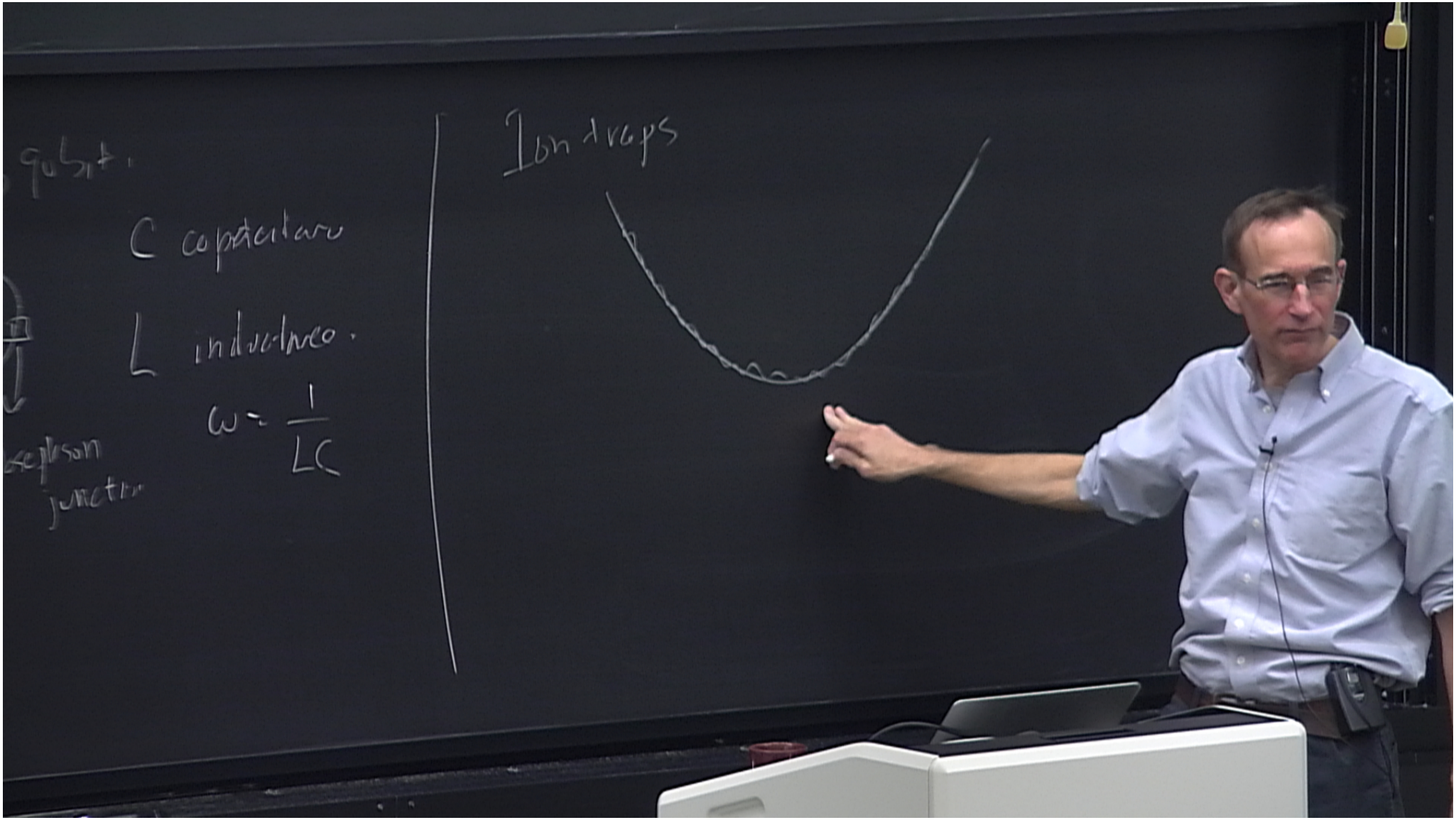

Superconducting qubit.
C capacitance
L inductance.
$\omega \sim \frac{1}{LC}$

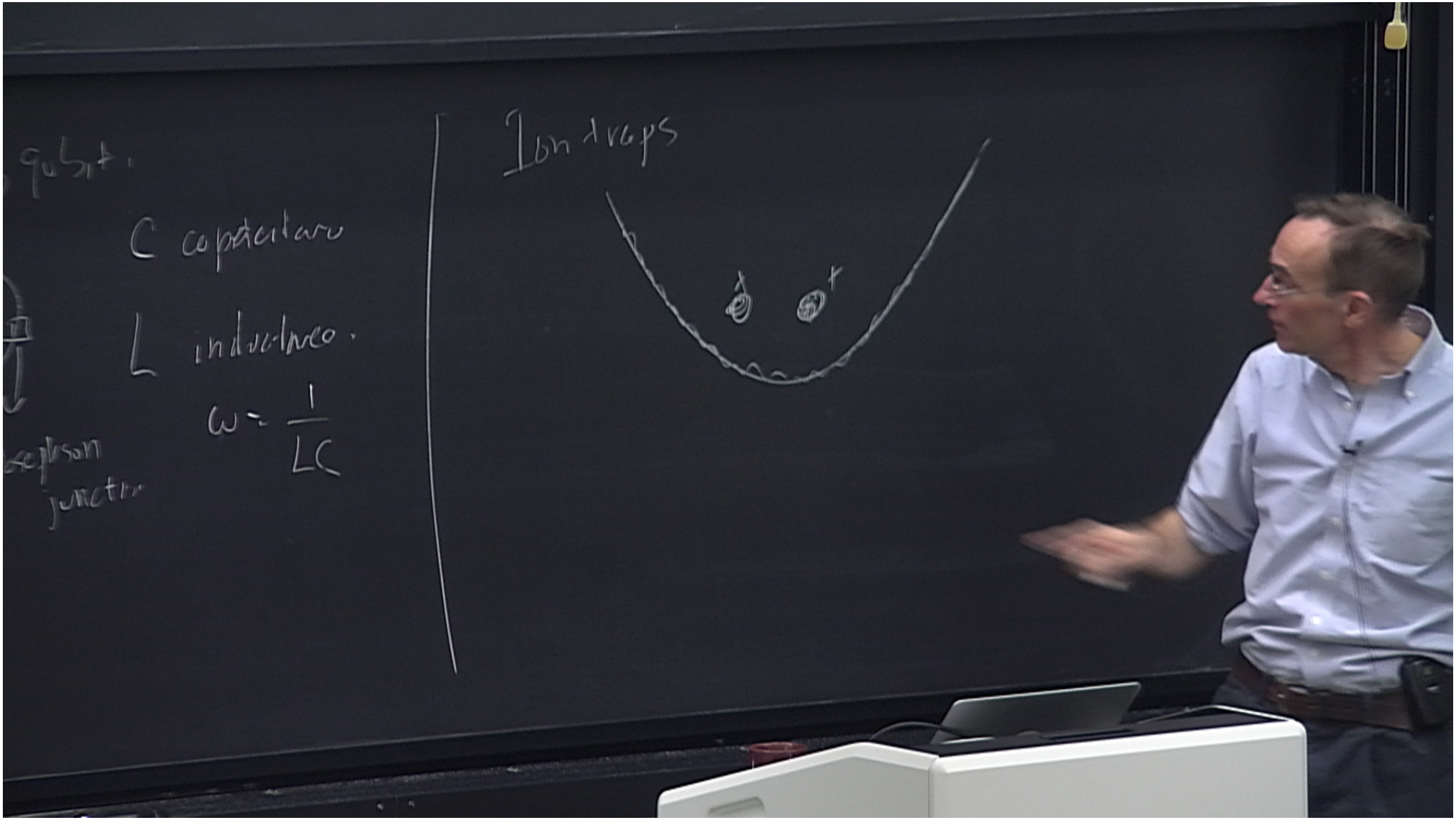

Superconducting qubit.
C capacit
L induc

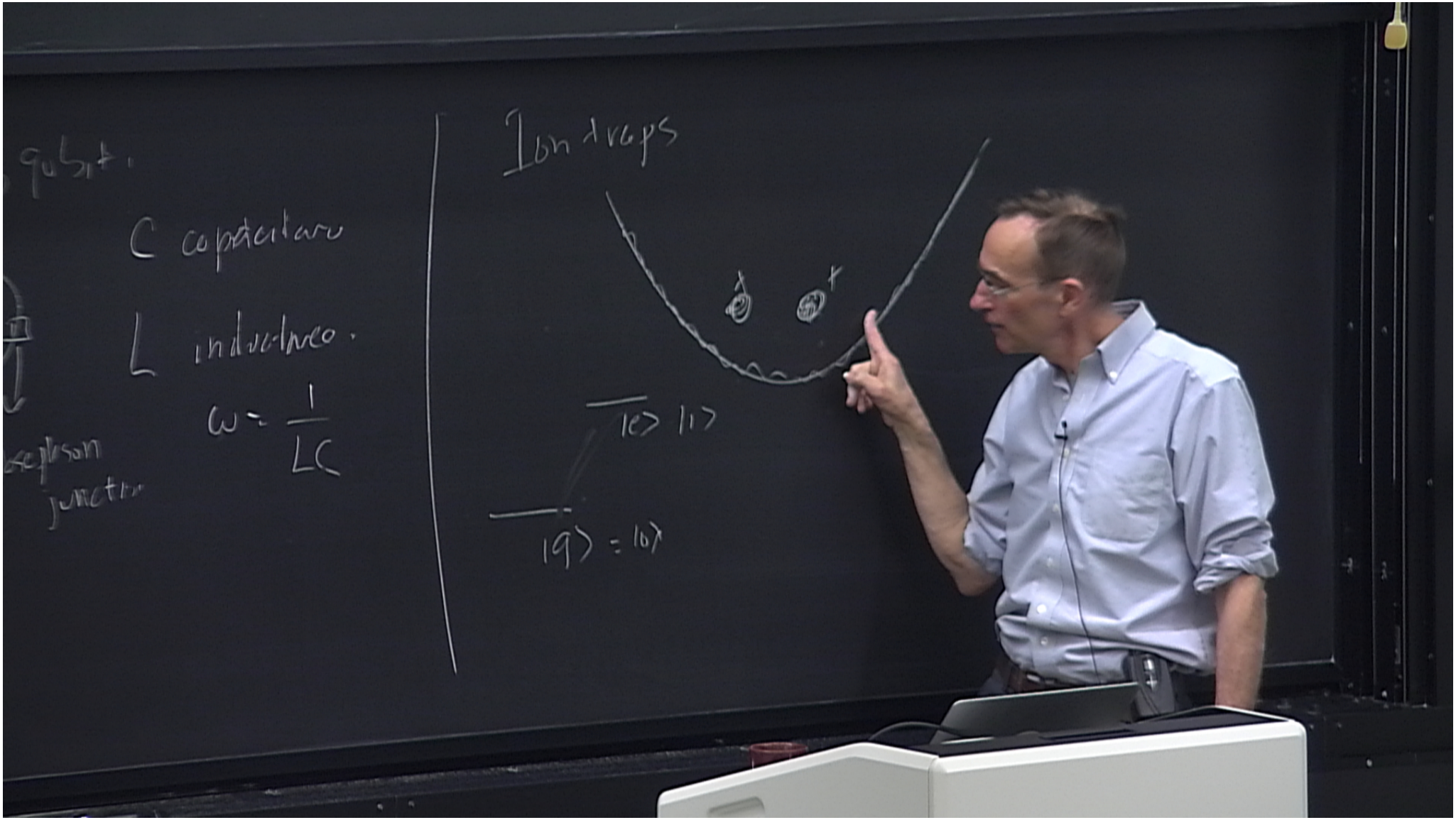

Superconducting qubit.
C capacitance
L inductance.
Josephson
junction

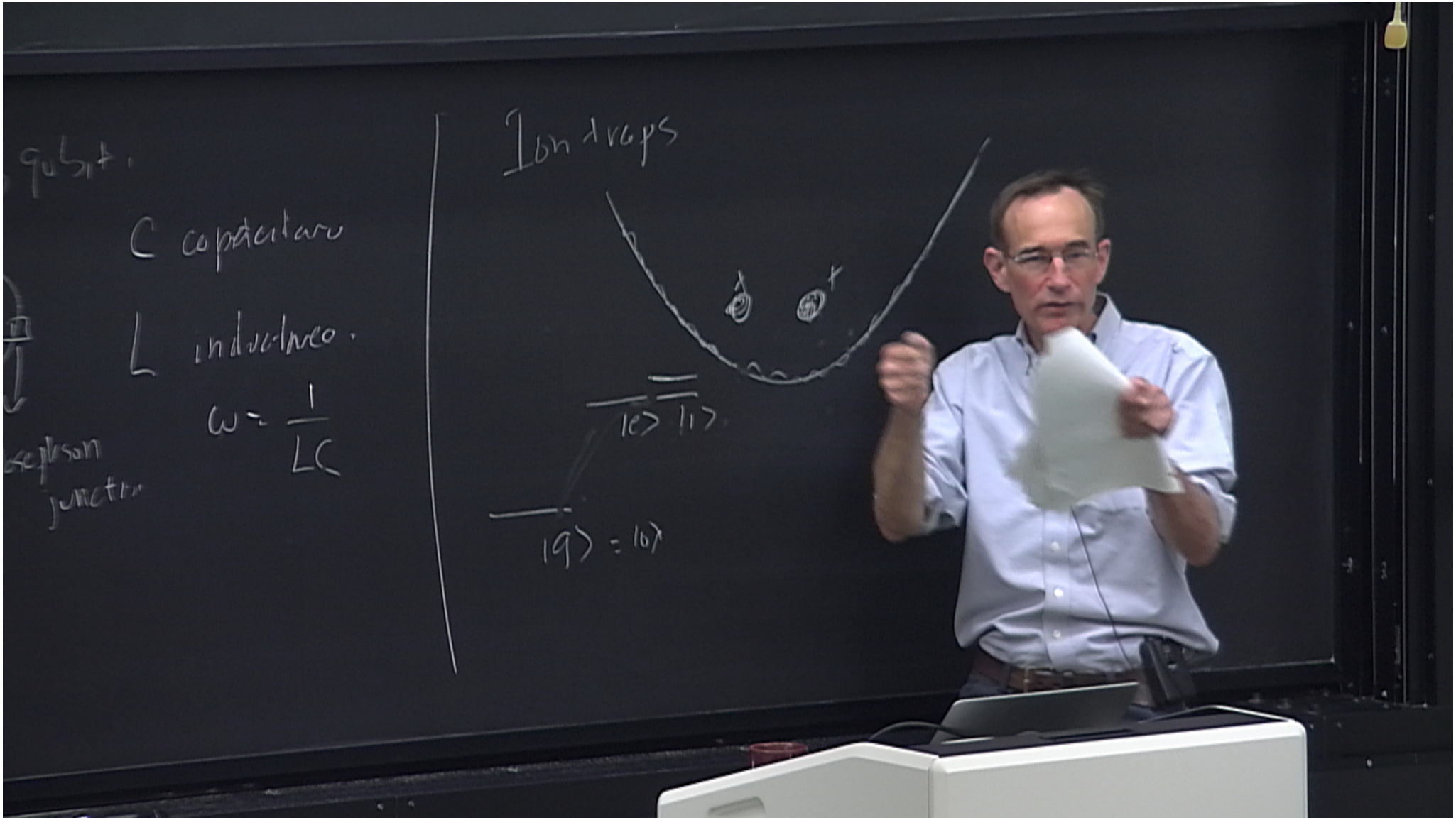

Superconducting qubit.
C capacitance
L inductance.
Josephson junction
$\omega = \frac{1}{LC}$

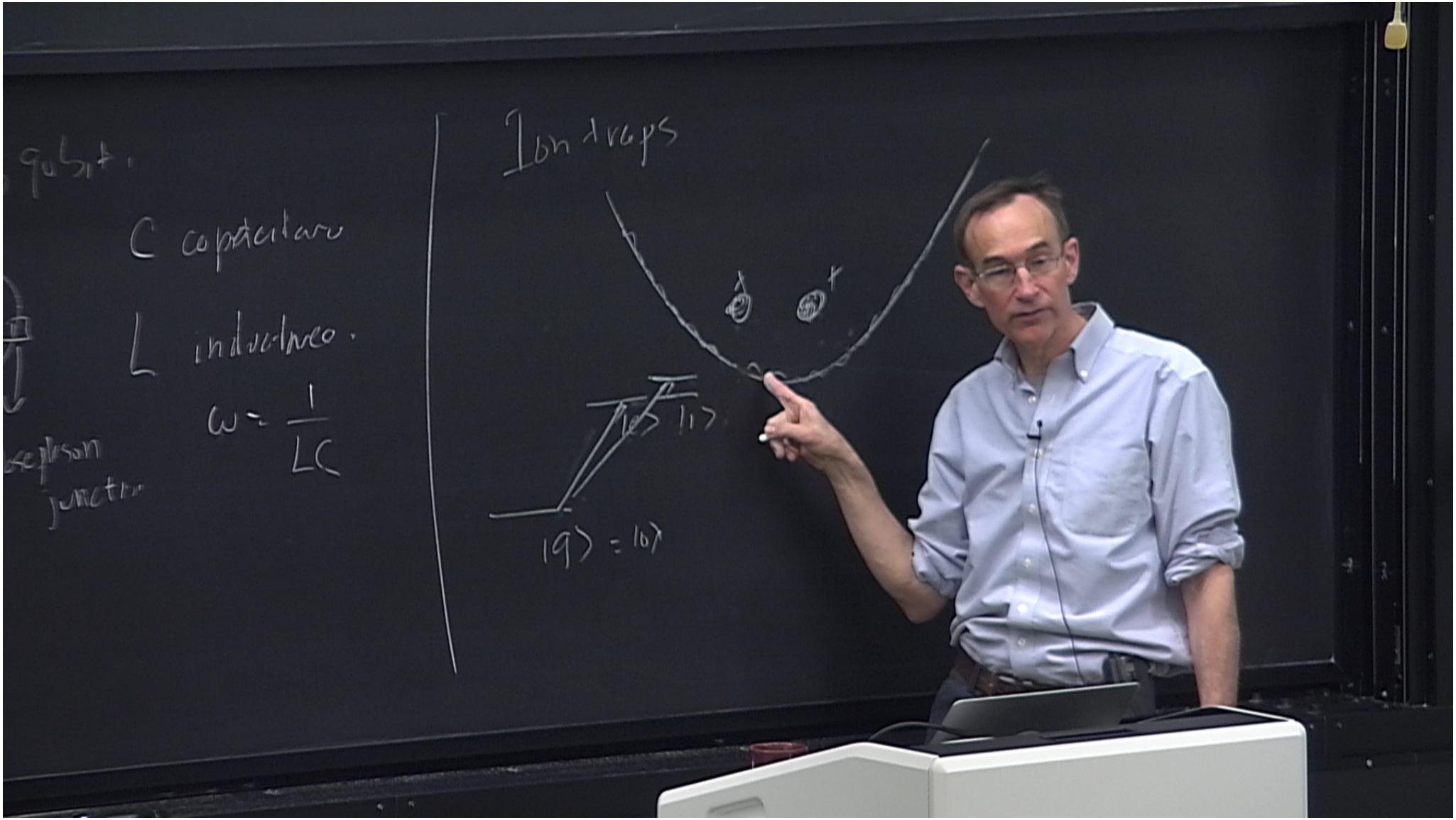

qubit.
C capacitance
L inductance.
$\omega = \frac{1}{LC}$
Josephson
junction
Ion traps

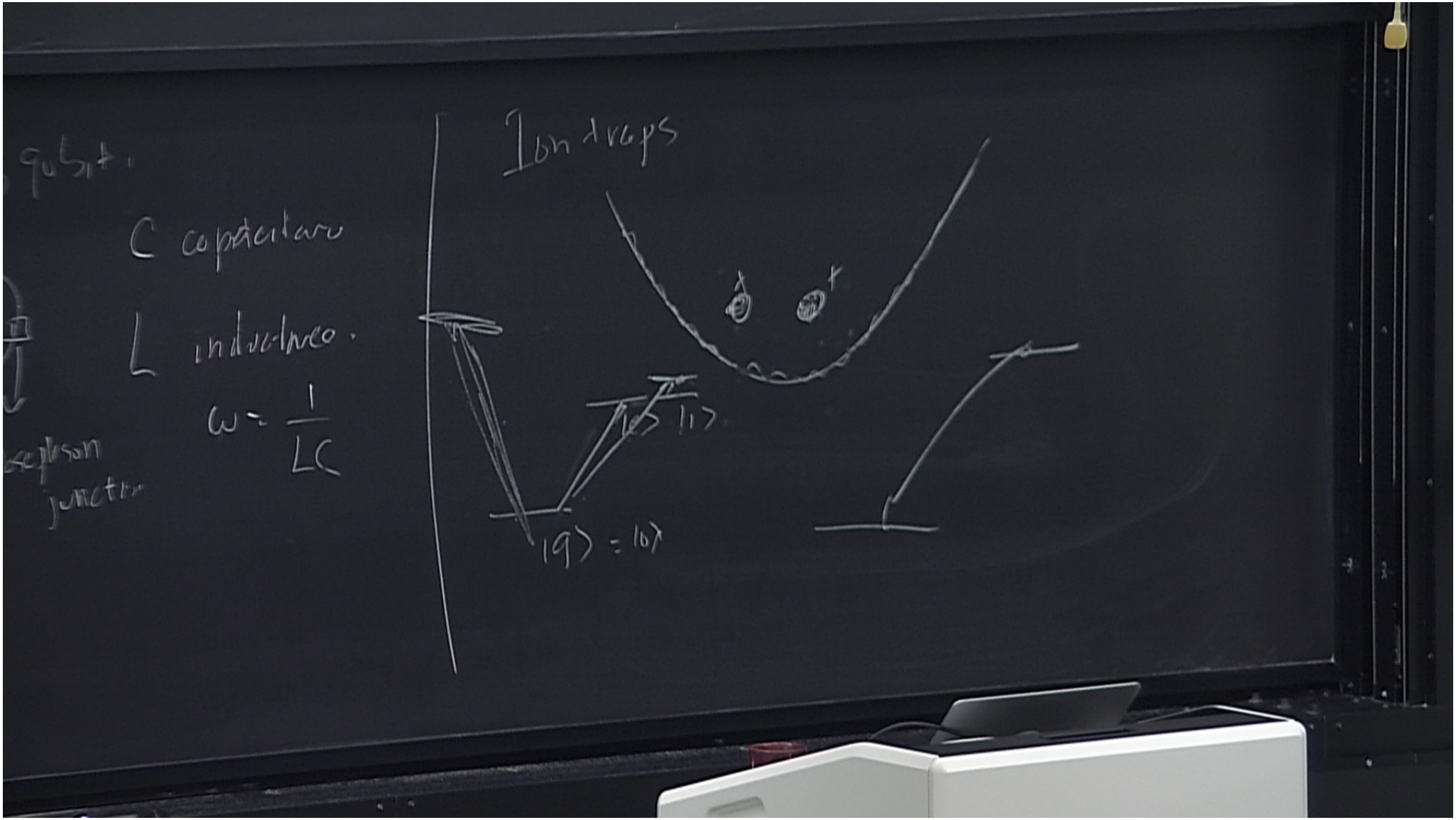

qubit.
C capacitance
L inductance
$\omega = \frac{1}{LC}$
Josephson
junction
Ion traps

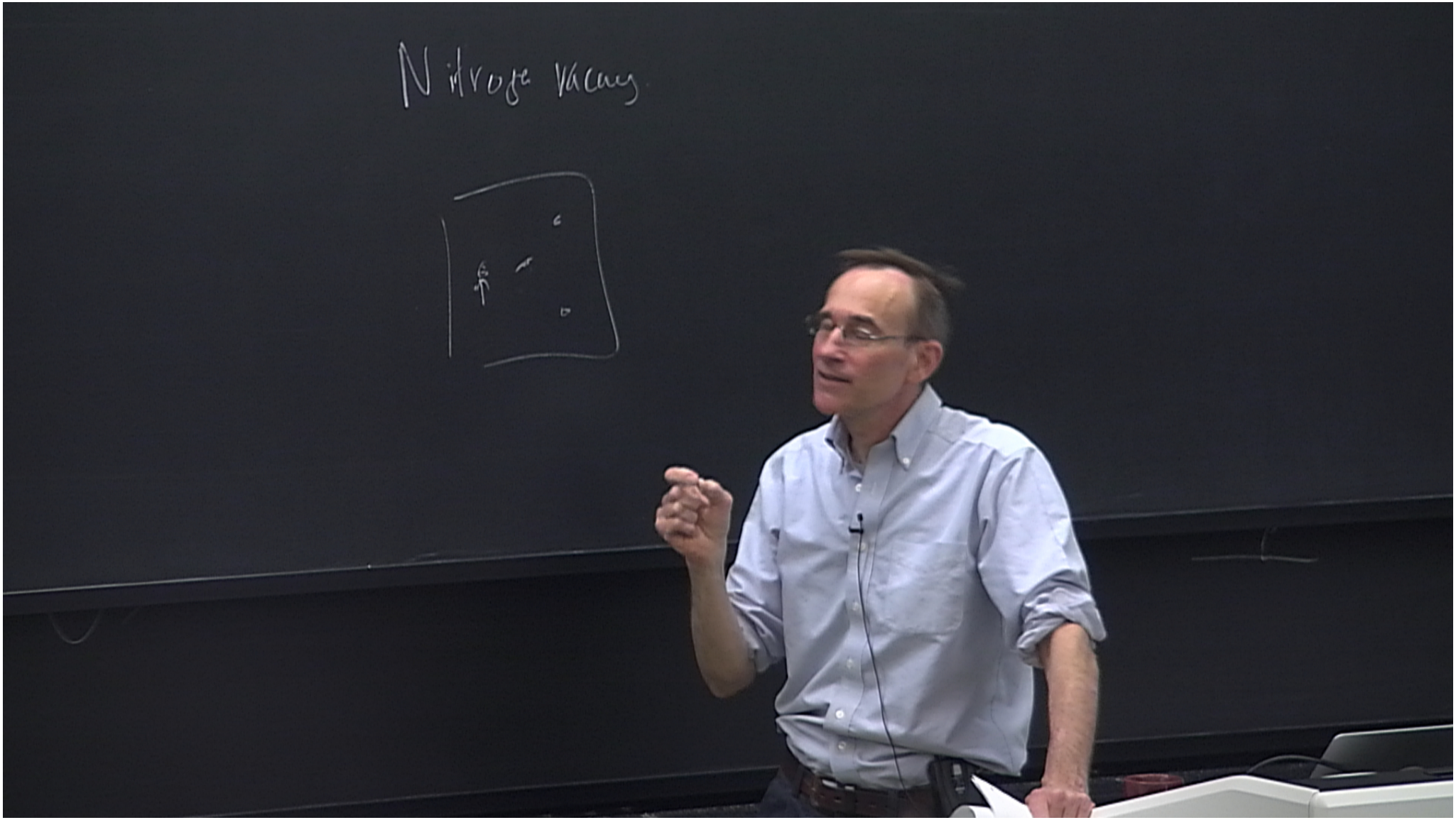

qubit.
C capacitance
L inductance.
$\omega = \frac{1}{LC}$
Ion traps

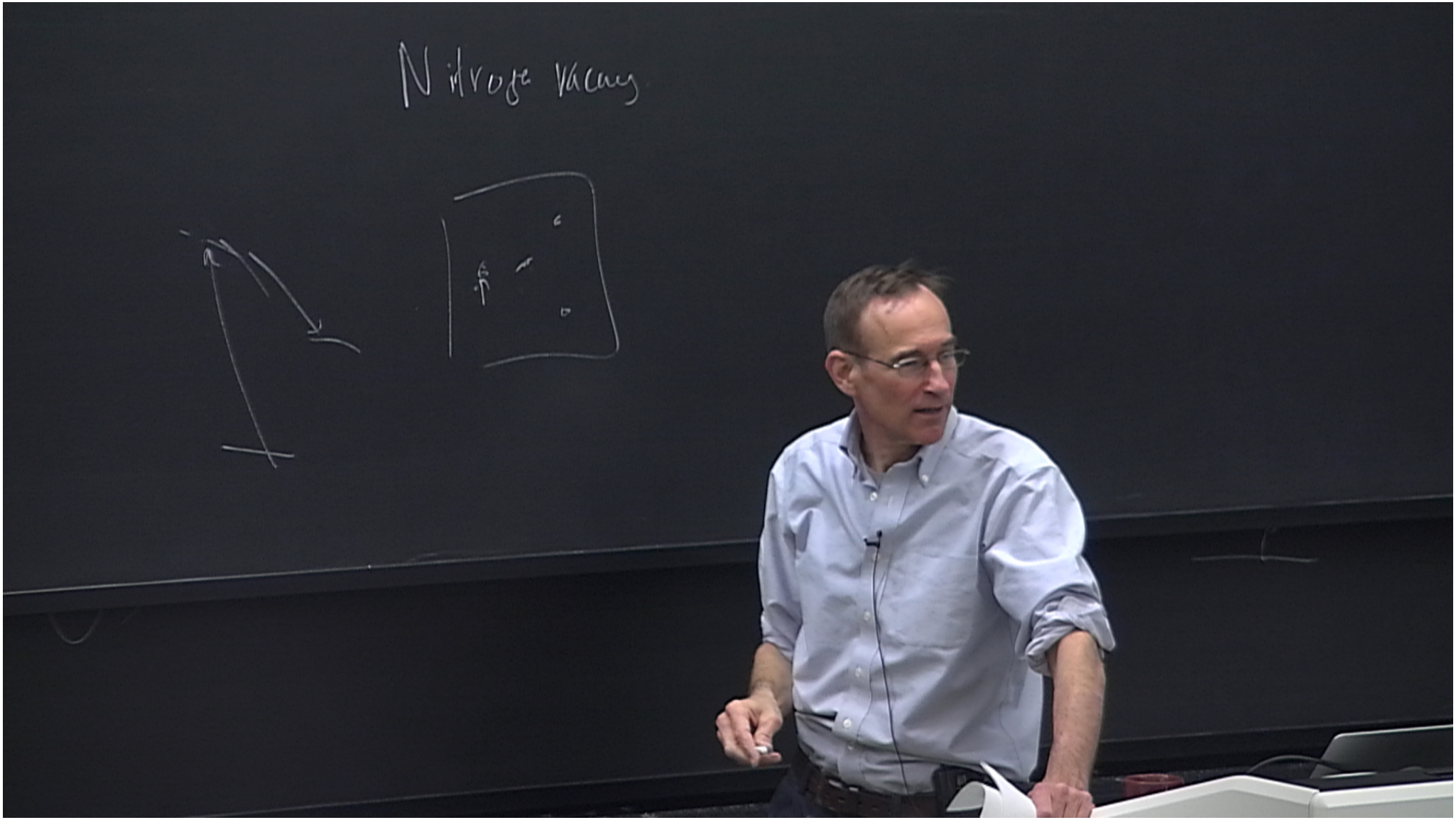

qubit.
C capacitance
L inductance
$\omega = \frac{1}{LC}$
Josephson junction
Ion traps
$|e\rangle$ $|r\rangle$
$|g\rangle = |0\rangle$

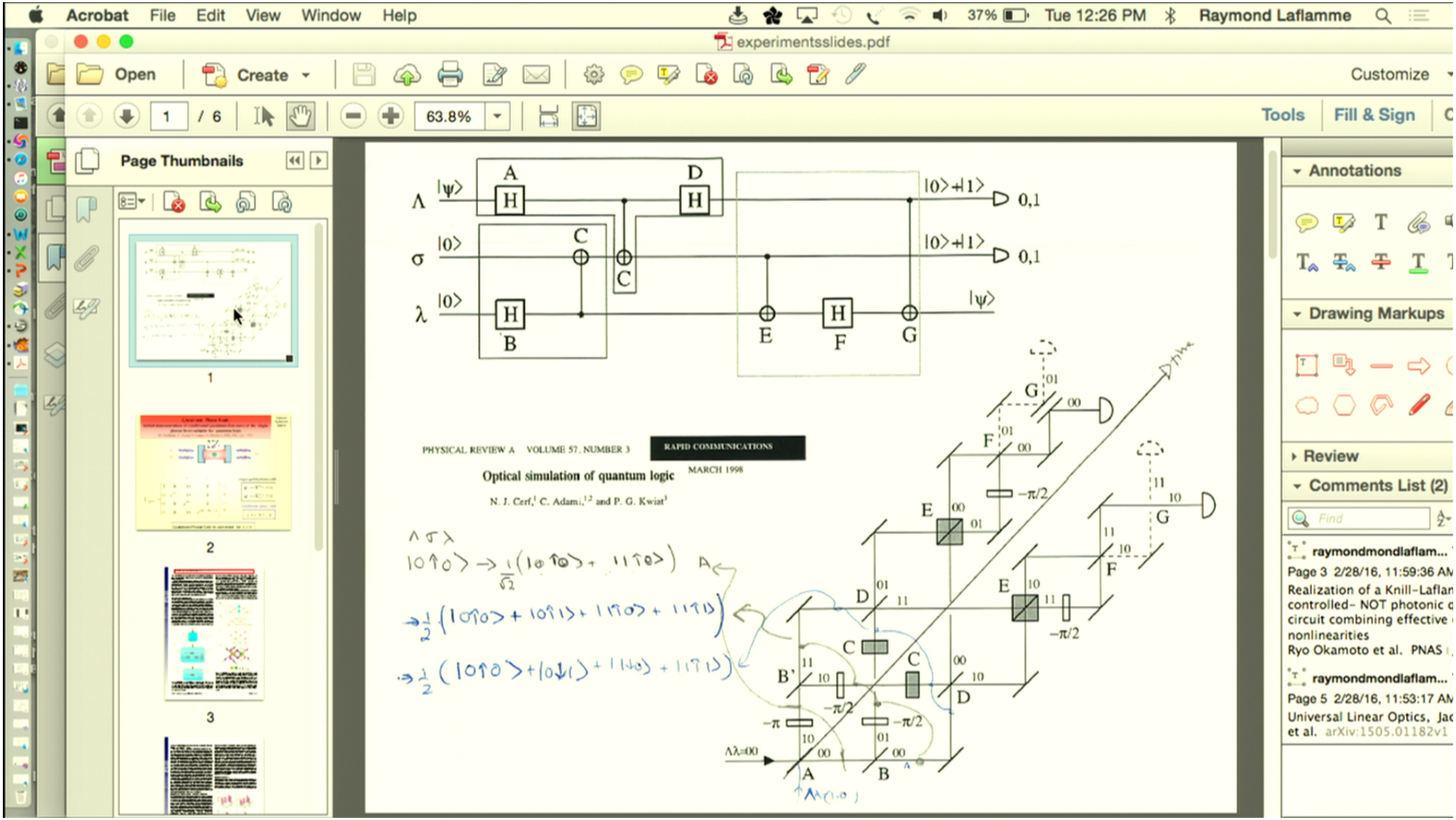

qubit.
C capacitance
L inductance.
$\omega = \frac{1}{LC}$
Ion traps
$|e\rangle$ $|i\rangle$
$|g\rangle = |0\rangle$


qubit.
C capacitance
L inductance
$\omega = \frac{1}{LC}$
Josephson junction
Ion traps
$|1\rangle$
$|g\rangle = |0\rangle$


qubit.
C capacitance
L inductance.
$\omega = \frac{1}{LC}$
Ion traps
$|1\rangle$
$|g\rangle = |0\rangle$


Nitrogen Vacancy


Nitrogen Vacancy


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Optical simulation of quantum logic
N. J. Cerf, C. Adami, and P. G. Kwiat
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Ryo Okamoto et al. PNAS
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Universal Linear Optics, Jac
et al. arXiv:1505.01182v1

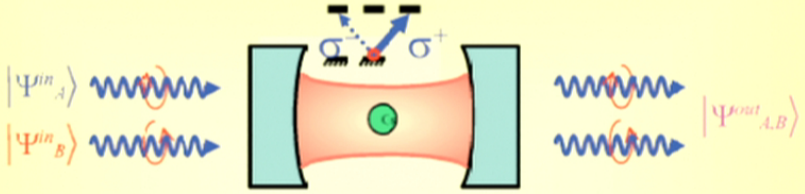
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Quantum Phase Gate

Initial demonstration of conditional quantum dynamics at the single photon level suitable for quantum logic

Q. Turchette, C. Hood, W. Lange, H. Mabuchi, HJK, PRL 78 (1995)

Caltech Quantum Optics



$$U_{QPG} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & e^{i\Phi_A} & 0 & 0 \\ 0 & 0 & e^{i\Phi_B} & 0 \\ 0 & 0 & 0 & e^{i(\Phi_A+\Phi_B+\Delta)} \end{bmatrix}$$

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single-qubit phase shifts

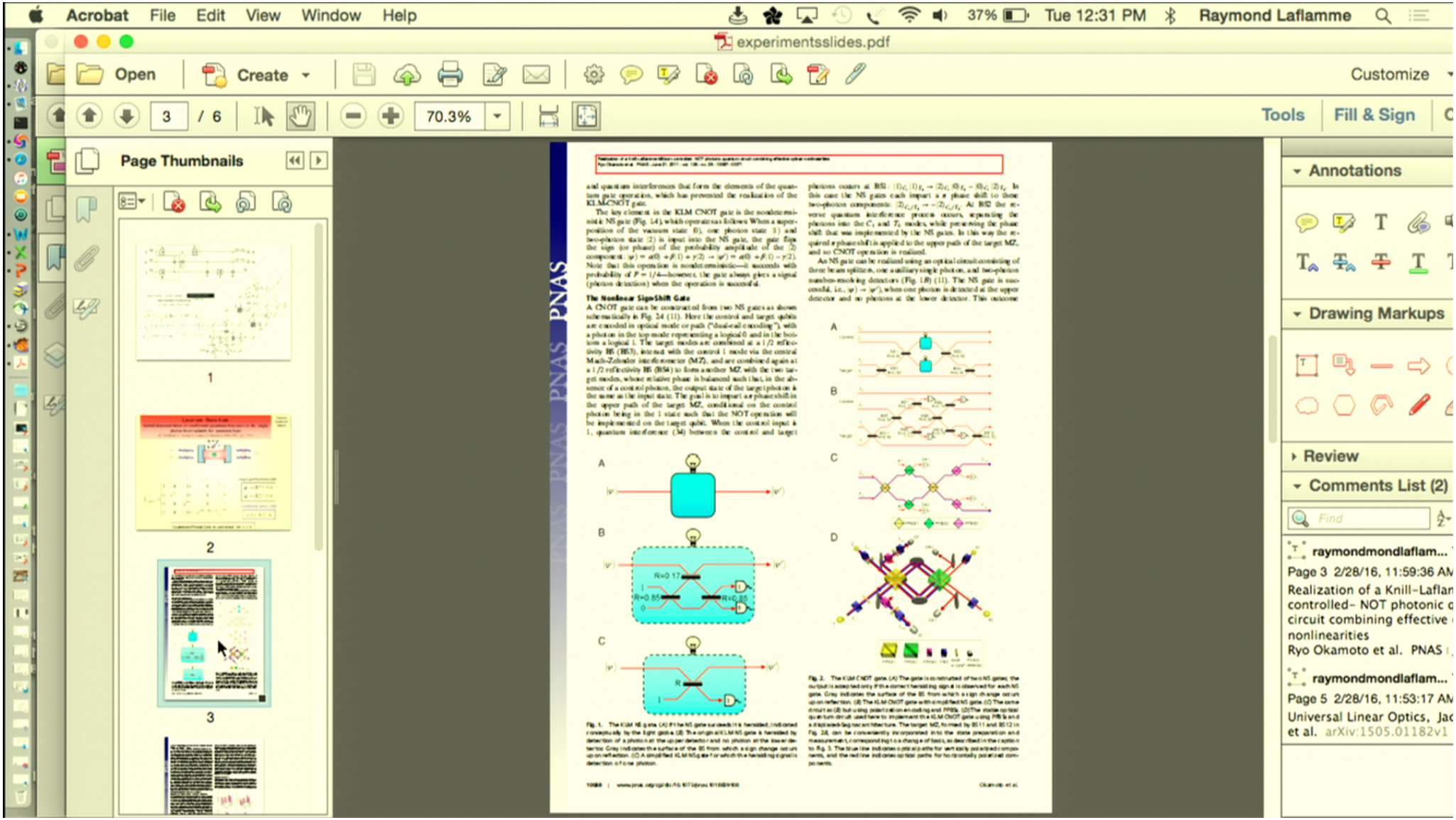
$$\phi_a \approx (17.5 \pm 1)^\circ$$
$$\phi_b \approx (12.5 \pm 1)^\circ$$

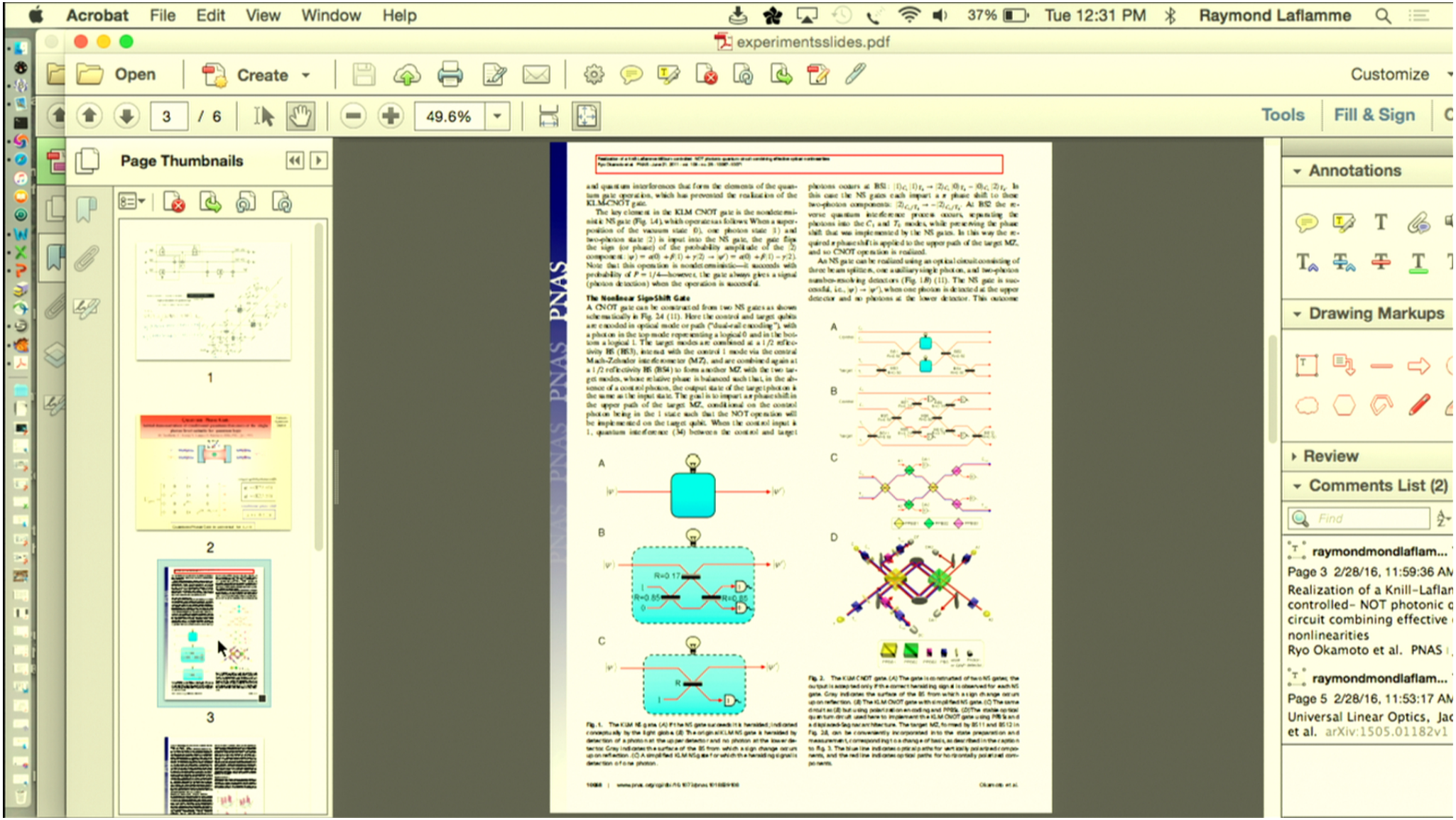
conditional phase shift

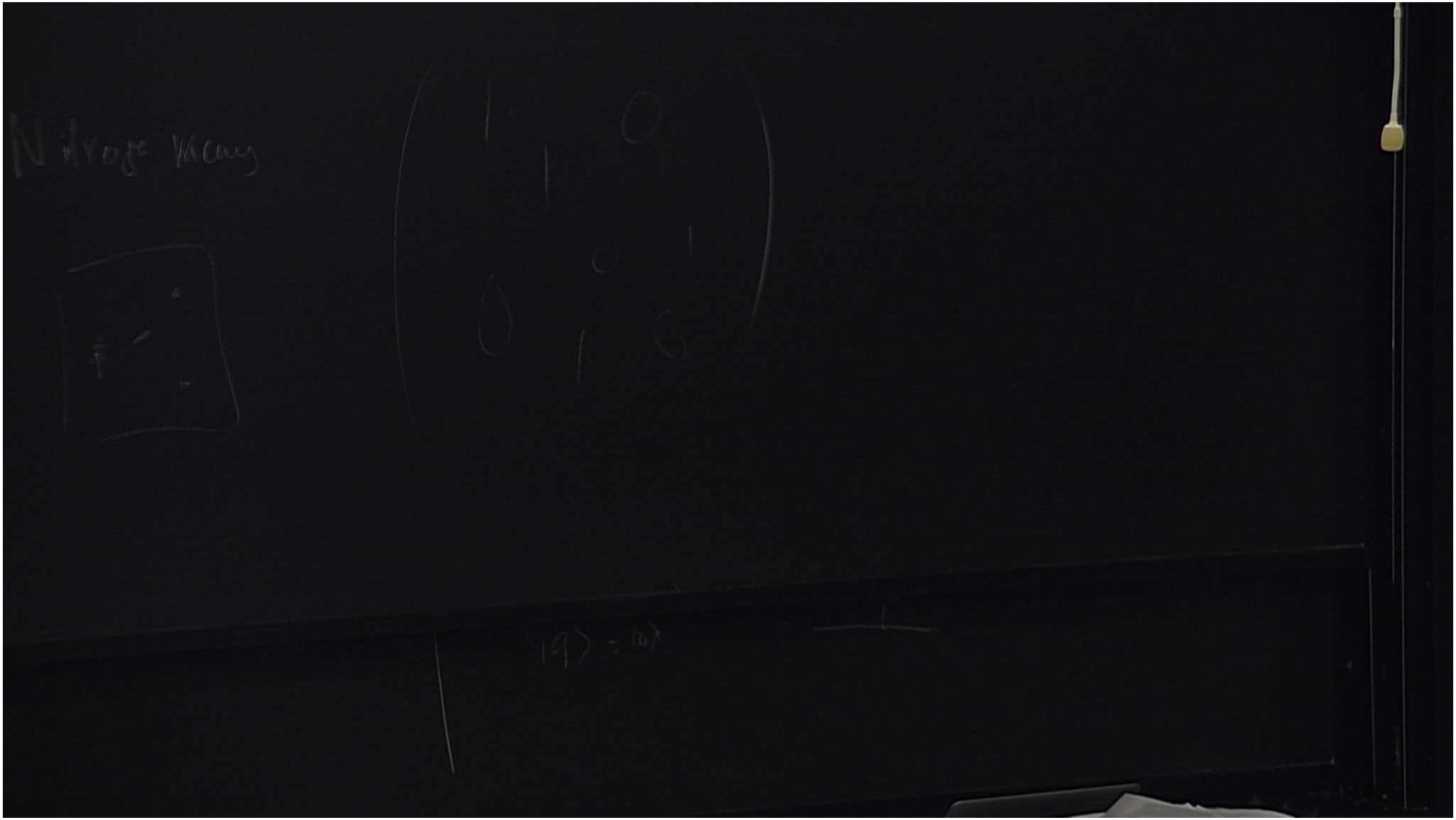
$$\Delta \approx (16 \pm 3)^\circ$$

Quantum Phase Gate is universal for $\Delta \neq 0$

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Progress in experimental QIP

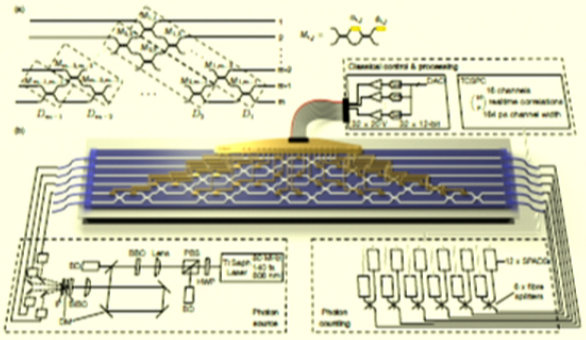


FIG. 1. Universal linear optical processor (LPU). (a) Decomposition of a fully parametrised unitary for an m-mode circuit to realise any LO operation. Sub-unitaries D_i consist of Mach-Zehnder interferometers $M_{i,j}$ (MZIs) built from phase shifters (yellow) and beam splitters, to control photon amplitudes ($\alpha_{i,j}$) and phases ($\phi_{i,j}$). (b) Multi-photon ensembles are generated via spontaneous parametric down-conversion (SPDC), comprising a BiBO crystal, dichroic mirrors (DM) and interference filter (IF), provided by a pulsed Ti:sapphire laser and second harmonic generation from a BIBO crystal. Photons are collected into polarisation maintaining fibres and delivered to the LPU via a packaged v-groove fibre array. The processor is constructed over six modes as a cascade of 15 Mach-Zehnder interferometers, controlled by 30 thermo-optic phase shifters, set by a digital-to-analogue converter (DAC) and actively cooled by a Peltier cooling unit. Photons are then out-coupled into a 2nd packaged VGA and sent to 6 (or 12 with fibre splitters for single-mode photon number resolving capability) single photon avalanche diodes (SPADe) and counted using a 12-channel time-correlated single-photon counting module (TCSPC). See Appendix for further details.

Such operation can be understood, with reference to the schematic shown in Fig. 1(a), as a sequence of m sub-unitaries D_i, each of which is guaranteed to enable transformation of the state of a photon input in its top mode into an arbitrary superposition of all its output modes. The top MZI in each D_i is set to retain the desired probability for a photon occupying the top mode, before imparting the desired phase on the top mode. The remainder of the photon undergoes a similar operation on the subsequent modes. Full reconfigurability is realised by feeding all output modes from one D_i into all but the uppermost input mode of the following D_{i-1} [17].

Realising such a scheme requires sub-wavelength stability and high fidelity components to support both classical and quantum interference — possibilities opened up by integrated quantum photonics [18–26]. A schematic of our LPU is shown in Fig. 1(b). The device, made with planar lightwave circuit (PLC) technology [27, 28], comprises an array of 30 silica-on-silicon waveguide directional couplers with 30 electronically controlled thermo-optic phase shifters, to form a cascade of 15 MZIs across six modes (see Appendix for further details). Such an LPU can implement any LO protocol, and here we focus on several protocols at the forefront of quantum information science and technology.

Quantum gates: With the addition of single photon sources and measurements, and rapid feed-forward of classical information, both the circuit [4] and measurement-based [8–10] models of digital quantum computing can be efficiently implemented with LO. Basic two-qubit processes are realised probabilistically with LO circuitry, therefore a key requirement for scalability is that a successful operation is heralded by the detection of ancillary photons, to signal that the processed photonic qubits are available for use in the larger architecture [29].

We programmed our device to implement a new compact four-photon scheme, suitable for measurement-based quantum computing, which generates the entangled state of two photonic qubits upon the detection of another two ancilla photons, schematically displayed in

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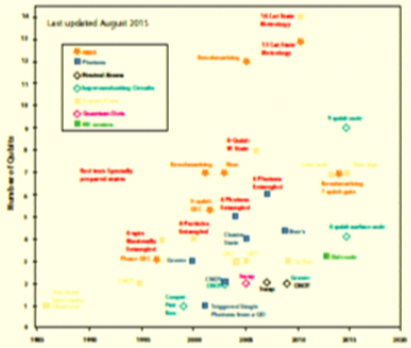
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Realization of a Knill-Laflan controlled- NOT photonic c circuit combining effective nonlinearities
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Universal Linear Optics, Jac et al. arXiv:1505.01182v1

Progress in experimental QIP

- # of qubits vs time



Adapted from Michael Mandelberg

- Increasing control of qubits

Table 1 | Current performance of various qubits

Type of qubit	T_2	Benchmarking (%)		References
		One qubit	Two qubits	
Infrared photon	0.1 ms	0.016	1	20
Trapped ion	15 s	0.48†	0.7*	104–106
Trapped neutral atom	3 s	5		107
Liquid molecule nuclear spins	2 s	0.01†	0.47†	108
e^- spin in GaAs quantum dot	3 µs	5		43, 57
e^- spins bound to ^{31}P:^{28}Si	0.6 s	5		49
^{29}Si nuclear spins in ^{28}Si	25 s	5		50
NV centre in diamond	2 ms	2	5	60, 61, 65
Superconducting circuit	4 µs	0.7†	10*	73, 79, 81, 109

Measured T_2 times are shown, except for photons where T_2 is replaced by twice the hold-time (comparable to T_1) of a telecommunication-wavelength photon in fibre. Benchmarking values show approximate error rates for single or multi-qubit gates. Values marked with asterisks are found by quantum process or state tomography, and give the departure of the fidelity from 100%. Values marked with daggers are found with randomized benchmarking[90]. Other values are rough experimental gate error estimates. In the case of photons, two-qubit gates fail frequently but success is heralded; error rates shown are conditional on a heralded success. NV, nitrogen vacancy.

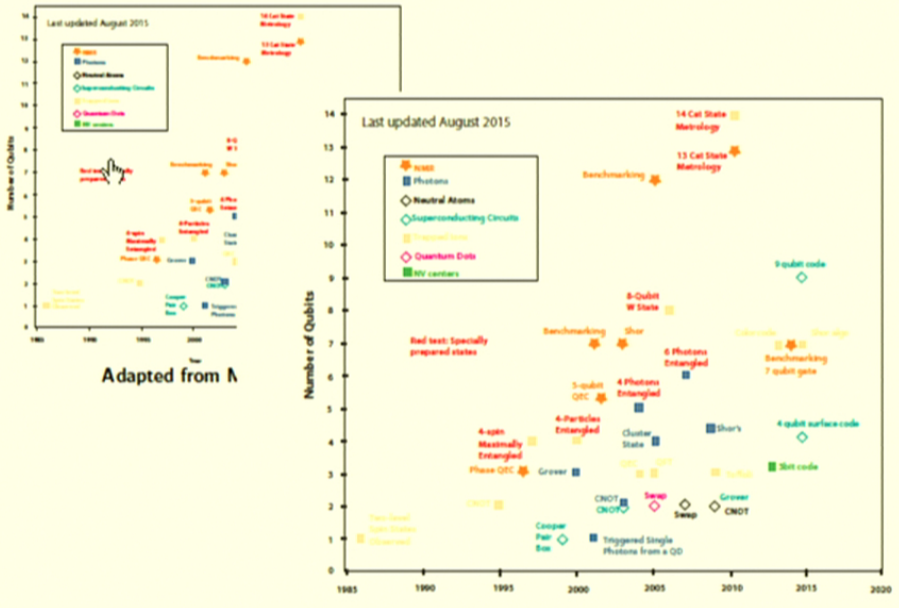
Ladd, T. D., et al., Nature, 464(7285), 45–53, 2010

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Annotations

Drawing Markups

Review

Comments List (2)

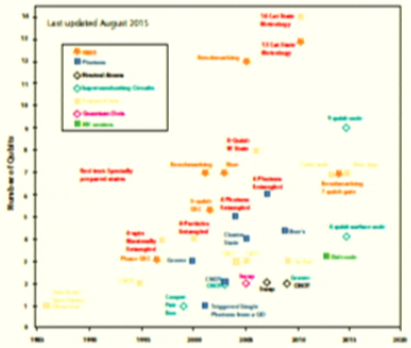
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