Title: Discrete Wigner Functions and Quantum Computation

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Abstract:

Discrete Wigner functions and quantum computational speed-up

PERIMETER INSTITUTE
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E.F.G., quant-ph/0405070
E.F.G., A. O. Pittenger, in preparation

Outline

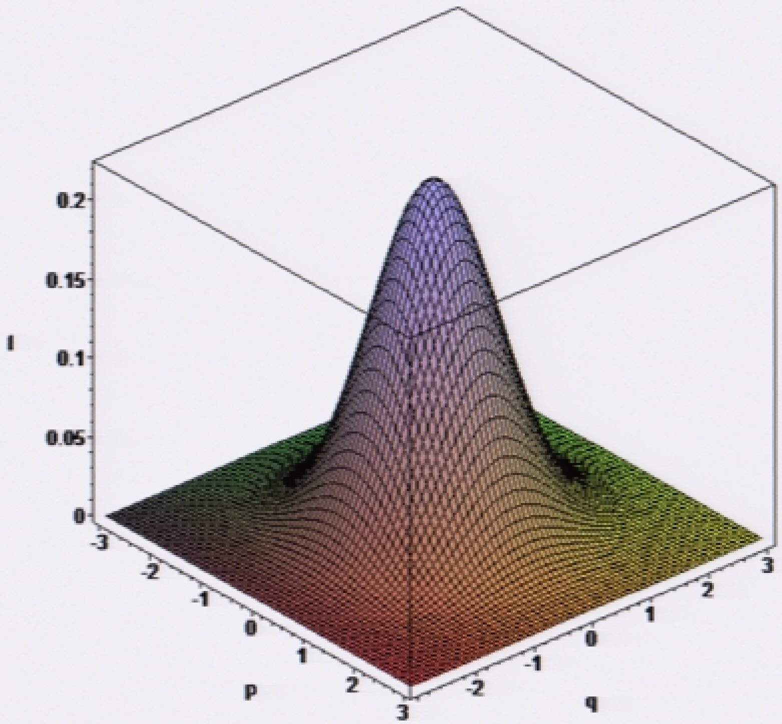
- Phase space representation of quantum states
  - the Wigner function W(q,p)
- Discrete Wigner functions W
  - proposal of Gibbons-Hoffman-Wootters
- Negativity of W and quantum computation
  - in the model of Bravyi and Kitaev
  - in the usual pure-state model
- Open problems

Classical phase space

- (q,p) are position and momentum of the particle

- a classical ensemble is described by a probability density -- the Liouville distribution f(q,p) in phase space

- Integrals over phase space give average properties of the ensemble

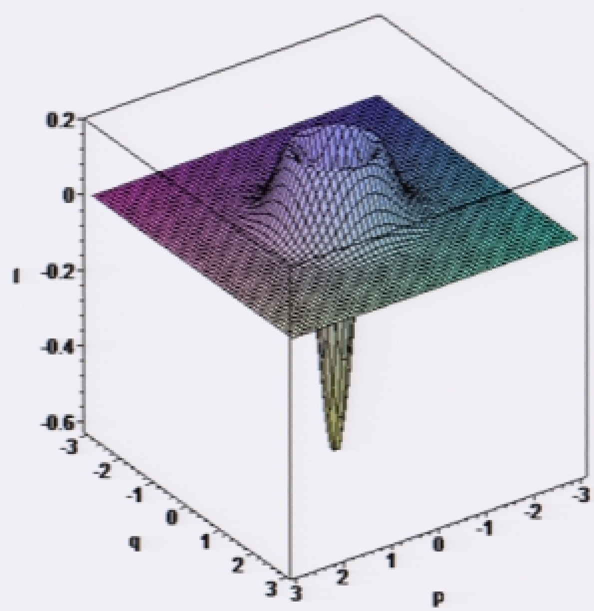


Quantum phase space and the Wigner function W(q,p)

- a quantum particle doesn't have (p,q) simultaneously well-defined

- yet, we can define a quasi-probability distribution W(q,p) in phase space with useful properties

- W(q,p) can assume negative values! Hence the term quasi-probability



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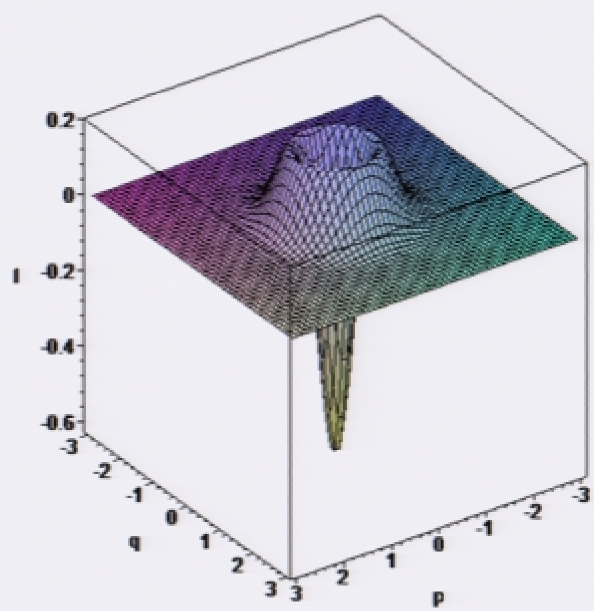

Properties of W(q,p)

- W(q,p) is tomographically complete, i.e. is equivalent to the density matrix

$$W(q,p) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} e^{ipx} \left\langle q - \frac{x}{2} \middle| \hat{\rho} \middle| q + \frac{x}{2} \right\rangle dx$$

- Correct marginal probability distributions:

$$\int W(q,p)\,dq = \langle p|\hat{\rho}|p\rangle, \int W(q,p)\,dp = \langle q|\hat{\rho}|q\rangle$$

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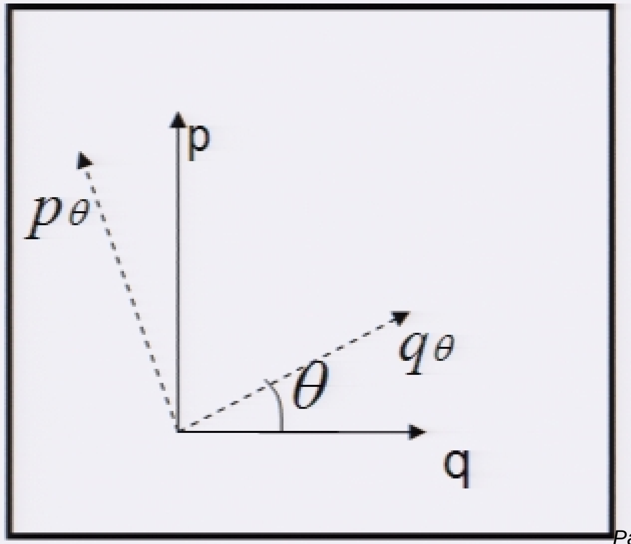
$$\int W(q,p)dq=\langle p|\hat{\rho}|p\rangle,\ \int W(q,p)dp=\langle q|\hat{\rho}|q\rangle$$

- This is true even for other quadratures:

$$\begin{cases} q_\theta = q\cos\theta + p\sin\theta \\ p_\theta = -q\sin\theta + p\cos\theta \end{cases}$$

$$\Rightarrow \langle q_\theta|\hat{\rho}|q_\theta\rangle =$$

$$\int W(q_\theta\cos\theta - p_\theta\sin\theta, q_\theta\sin\theta + p_\theta\cos\theta)dp_\theta$$

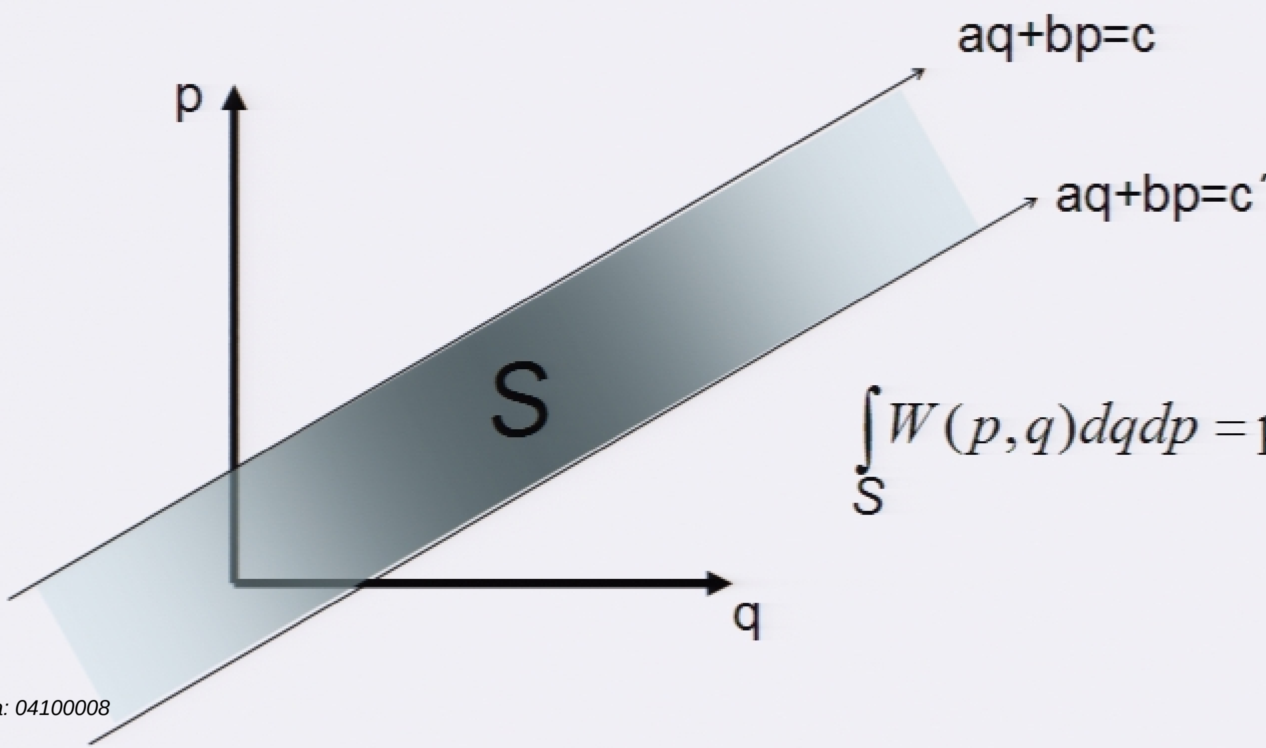


More properties of W(q,p)

- Expected values of symmetrical operators can be calculated as in the classical case. Example:

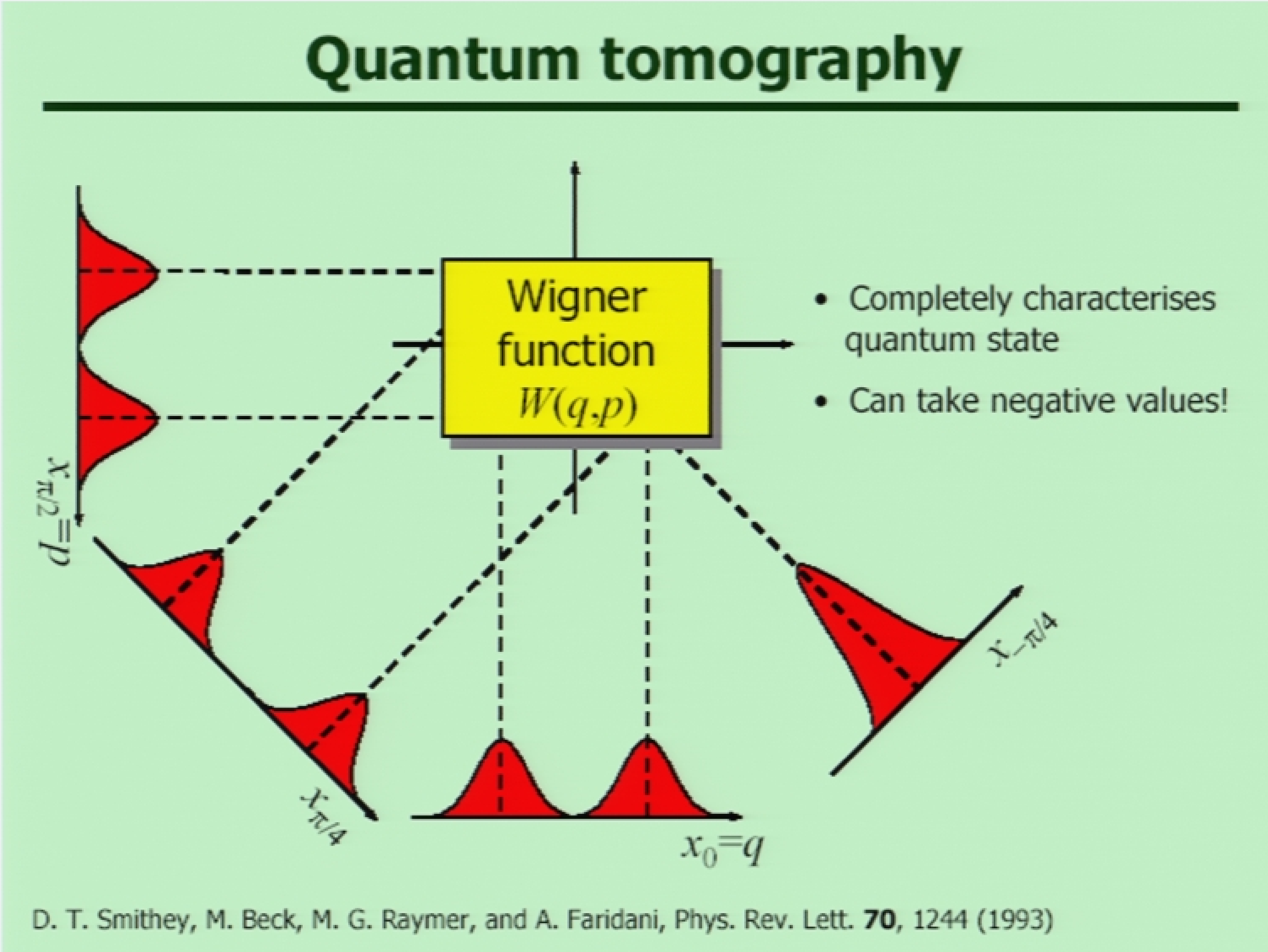
$$Tr[\hat{\rho}(\hat{q}^2\hat{p}+\hat{q}\hat{p}\hat{q}+\hat{p}\hat{q}^2)/3]=\int dqdpW(q,p)q^2p$$

- Also true for integrals over strips in phase space:



$$\int_S W(p,q)dqdp=\mathrm{prob}\left(c\le v(a\hat{q}+b\hat{p})\le c'\right)$$

Tomography: reconstructing quantum 'stuff' from shadows



Courtesy: K. Banaszek

Motivating question

- What is non-classical about states with negative values of $W(q,p)$?

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> Here I investigate this question using Wigner functions defined for **discrete** Hilbert spaces, i.e. qubits, qutrits, etc.

Discrete Wigner functions for *d*-dimensional Hilbert space

- Different proposals for discrete Wigner functions: Feynman `87, Wootters `87, Galetti and de Toledo Pisa `88, …
- A particularly elegant formulation is the one by Wootters, extended recently by **Gibbons, Hoffman and Wootters** (quant-ph/0401155).

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Ingredients:

1. Discrete phase space (d x d array)

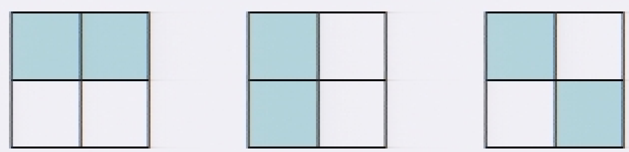
2. (d+1) striations of the phase space
   (= partitions of phase space into parallel lines)

3. (d+1) Mutually Unbiased Bases (MUB's)

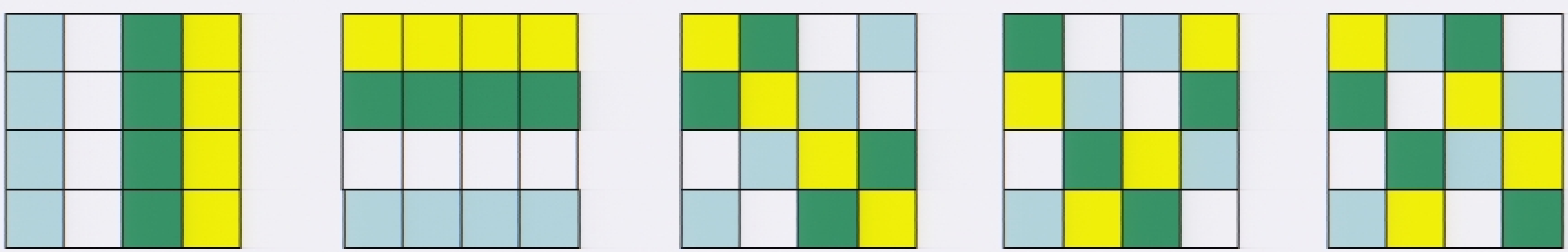
Parallel lines in a *dxd* discrete phase space

- **Line**: set of *d* phase-space points.
- **Striation**: partition of the discrete phase-space into parallel lines.
- Gibbons *et al.* use **finite fields** to define (d+1) striations of the *dxd* phase space with properties:
  - there exists only one parallel line containing an arbitrary pair of points;
  - given a line L and a point P outside it, there exists only one line parallel to L containing P;
  - two non-parallel lines intersect at exactly one point.

- Examples
  - the 3 striations for a qubit (*d*=2):



  - the 5 striations for *d*=4:



Mutually unbiased bases in d-dimensional Hilbert space

- Let's take different bases for a d-dimensional Hilbert space:

$$\text{MUB1} = \{|\alpha_{1,1}\rangle, |\alpha_{1,2}\rangle, \ldots, |\alpha_{1,d}\rangle\}, \quad |\langle\alpha_{1,k}|\alpha_{1,l}\rangle|^2 = \delta_{k,l}$$

$$\text{MUB2} = \{|\alpha_{2,1}\rangle, |\alpha_{2,2}\rangle, \ldots, |\alpha_{2,d}\rangle\}, \quad |\langle\alpha_{2,k}|\alpha_{2,l}\rangle|^2 = \delta_{k,l}$$

$$\vdots$$

- They are called mutually unbiased bases (MUB's) if:

$$|\langle\alpha_{i,k}|\alpha_{j,l}\rangle|^2 = \begin{cases} \frac{1}{d} & \text{for } \ i \neq j \\ \delta_{k,l} & \text{for } \ i = j \end{cases}$$

- **Facts:**
  - (Wootters and Fields): for $d=p^k$ (p prime), there exist (d+1) MUB's.
  - Projectors onto the basis states of these (d+1) MUB's form a tomographically complete set of observables.

Defining a class of discrete Wigner functions

- Associations:

MUB's and striations: $\text{MUB}_i \longleftrightarrow$ Striation i

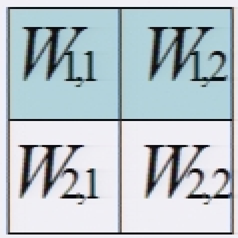
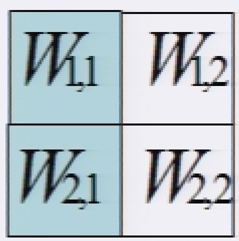
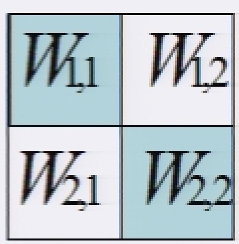
MUB projectors and lines: $|\alpha_{i,j}\rangle\langle\alpha_{i,j}| \longleftrightarrow$ j´th line in i'th striation

- Imposing the following requirement defines W uniquely:

$$p_{i,j} \equiv Tr\left(\hat{\rho}\,|\alpha_{i,j}\rangle\langle\alpha_{i,j}|\right) = \sum_{r \in line(i,j)} W(r)$$

Each choice of associations picks one definition of Wigner function. Gibbons-Hoffman-Wootters use the recipe above to define a ***class*** of Wigner functions.

Example: *W* for a qubit

	Striations	Requirements:
1:		$\sum \blacksquare = \text{prob}\left(\sigma_x = +1\right)$ $\sum \square = \text{prob}\left(\sigma_x = -1\right)$
2:		$\sum \blacksquare = \text{prob}\left(\sigma_y = +1\right)$ $\sum \square = \text{prob}\left(\sigma_y = -1\right)$
3:		$\sum \blacksquare = \text{prob}\left(\sigma_z = +1\right)$ $\sum \square = \text{prob}\left(\sigma_z = -1\right)$

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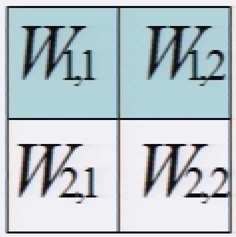
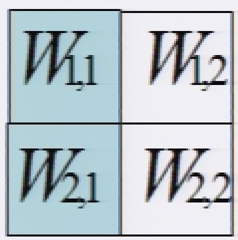
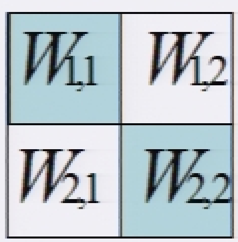
1:		$W_{1,1} + W_{1,2} = p_{1,1}$ $W_{2,1} + W_{2,2} = p_{1,2}$
2:		$W_{1,1} + W_{2,1} = p_{2,1}$ $W_{1,2} + W_{2,2} = p_{2,2}$
3:		$W_{1,1} + W_{2,2} = p_{3,1}$ $W_{1,2} + W_{2,1} = p_{3,2}$

Note $: p_{i,j} = Tr\left[\hat{\rho} \left| \alpha_{i,j} \right\rangle \left\langle \alpha_{i,j} \right| \right]$

Finding the resulting Wigner function *W*

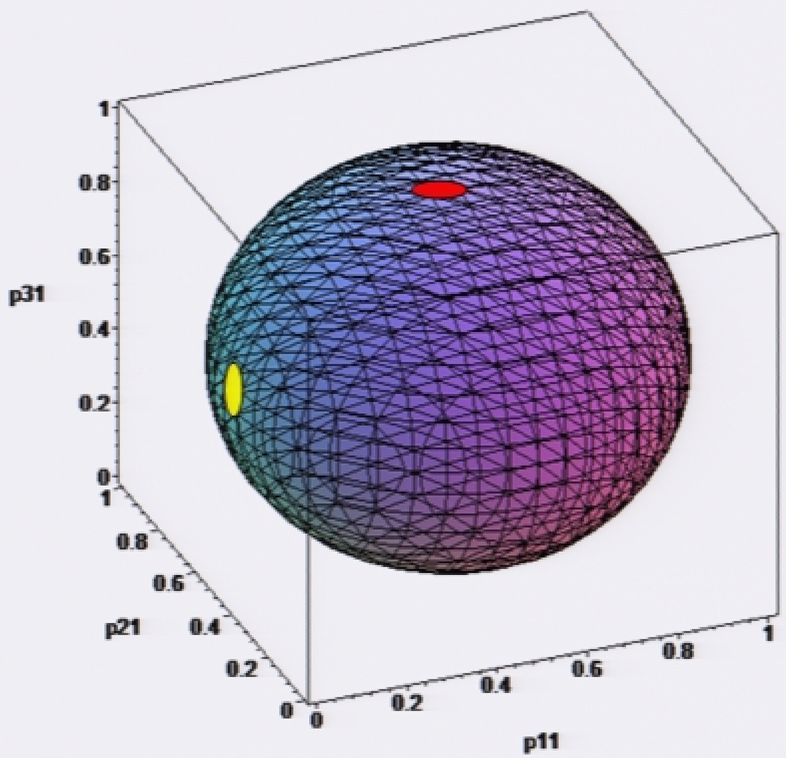
- We solve the system of equations:

$$\begin{cases} W_{1,1} + W_{1,2} = p_{1,1} \\ W_{2,1} + W_{2,2} = p_{1,2} = 1 - p_{1,1} \\ W_{1,1} + W_{2,1} = p_{2,1} \\ W_{1,2} + W_{2,2} = p_{2,2} = 1 - p_{2,1} \\ W_{1,1} + W_{2,2} = p_{3,1} \\ W_{1,2} + W_{2,1} = p_{3,2} = 1 - p_{3,1} \end{cases} \Rightarrow$$

$$\begin{aligned} W_{1,1} &= \tfrac{1}{2}\left(p_{1,1} + p_{2,1} + p_{3,1} - 1\right) \\ W_{1,2} &= \tfrac{1}{2}\left(p_{1,1} + p_{2,2} + p_{3,2} - 1\right) \\ W_{2,1} &= \tfrac{1}{2}\left(p_{1,2} + p_{2,1} + p_{3,2} - 1\right) \\ W_{2,2} &= \tfrac{1}{2}\left(p_{1,2} + p_{2,2} + p_{3,1} - 1\right) \end{aligned}$$

$$W = \begin{array}{|c|c|} \hline \tfrac{1}{2}\left(p_{1,1} + p_{2,1} + p_{3,1} - 1\right) & \tfrac{1}{2}\left(p_{1,1} + p_{2,2} + p_{3,2} - 1\right) \\ \hline \tfrac{1}{2}\left(p_{1,2} + p_{2,1} + p_{3,2} - 1\right) & \tfrac{1}{2}\left(p_{1,2} + p_{2,2} + p_{3,1} - 1\right) \\ \hline \end{array}$$

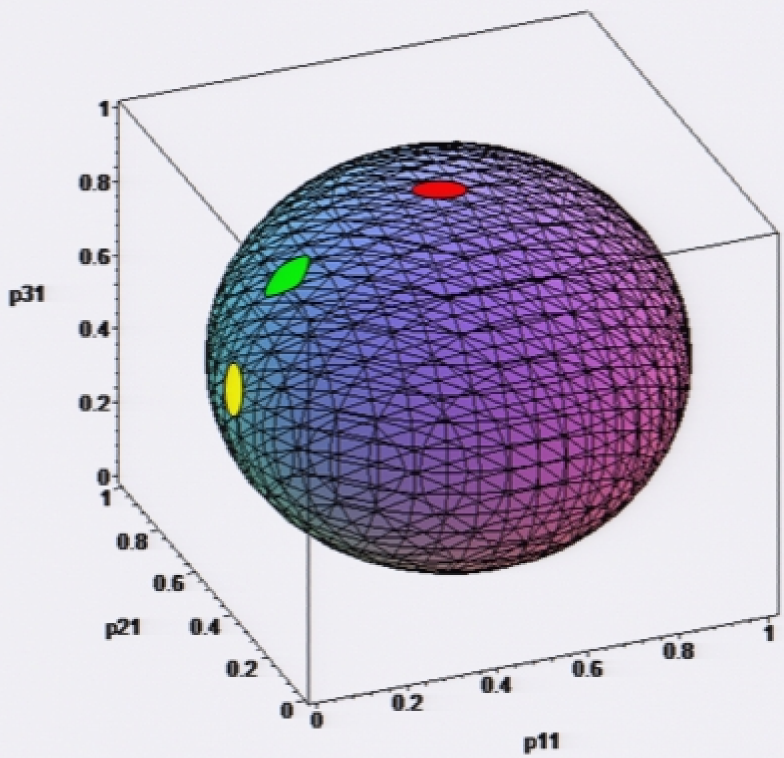
Wigner function for some states



$$W(\color{red}{\bullet}) = \begin{array}{|c|c|} \hline \tfrac{1}{2} & 0 \\ \hline 0 & \tfrac{1}{2} \\ \hline \end{array}$$

$$W(\color{yellow}{\bullet}) = \begin{array}{|c|c|} \hline 0 & 0 \\ \hline \tfrac{1}{2} & \tfrac{1}{2} \\ \hline \end{array}$$

Wigner function for some states



$W($ ● (red) $) =$

½	0
0	½

$W($ ● (yellow) $) =$

0	0
½	½

$W($ ● (green) $) =$

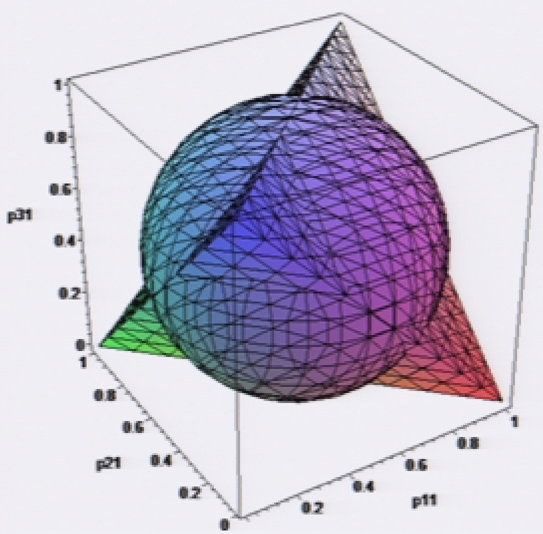
0.25	−0.10
0.25	0.60

Negativity of *W*!

One-qubit states with non-negative *W*

For one particular definition:

$$\begin{cases} p_{1,1} + p_{2,1} + p_{3,1} \geq 1 \\ p_{1,1} - p_{2,1} - p_{3,1} \geq -1 \\ -p_{1,1} + p_{2,1} - p_{3,1} \geq -1 \\ -p_{1,1} - p_{2,1} + p_{3,1} \geq -1 \end{cases}$$



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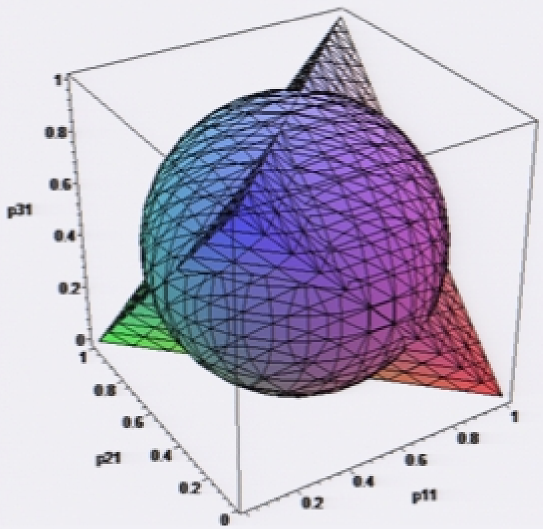
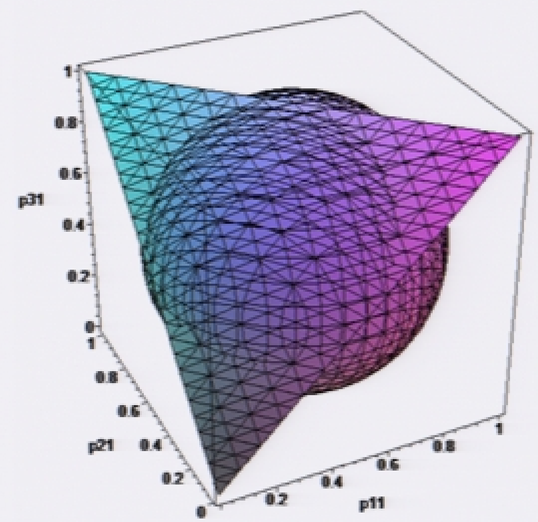


Swap lines in 3rd striation

$$p_{3,1}\leftrightarrow 1-p_{3,1}$$

For a different definition of *W*:

$$\begin{cases} p_{1,1}+p_{2,1}-p_{3,1}\geq 0 \\ p_{1,1}-p_{2,1}+p_{3,1}\geq 0 \\ -p_{1,1}+p_{2,1}+p_{3,1}\geq 0 \\ -p_{1,1}-p_{2,1}-p_{3,1}\geq -2 \end{cases}$$



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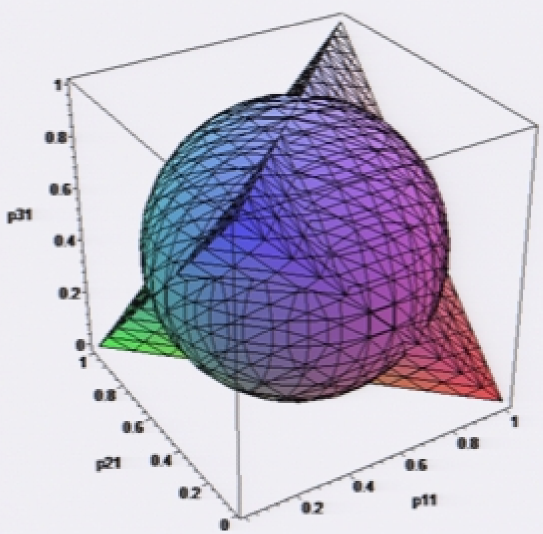

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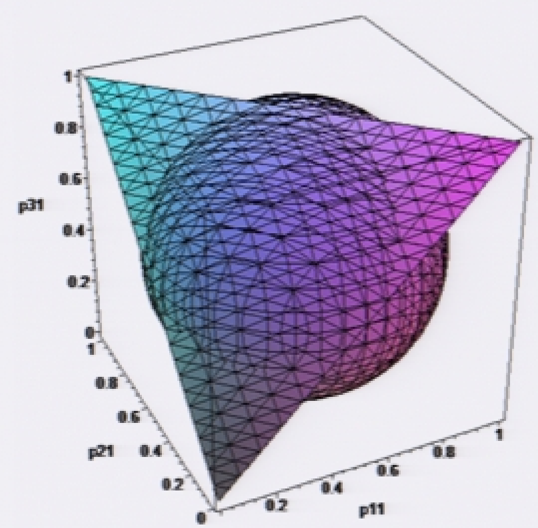
$$p_{3,1} \leftrightarrow 1 - p_{3,1}$$

The set of states with non-negative W depends on the definition we pick

For a different definition of W:

$$\begin{cases} p_{1,1} + p_{2,1} - p_{3,1} \geq 0 \\ p_{1,1} - p_{2,1} + p_{3,1} \geq 0 \\ -p_{1,1} + p_{2,1} + p_{3,1} \geq 0 \\ -p_{1,1} - p_{2,1} - p_{3,1} \geq -2 \end{cases}$$



‘Classical’ states in *d* dimensions -- definition

- Let’s define a set C_d of ‘classical’ states with properties:

  1- is based on non-negativity of *W* (‘no negative probabilities’);

  2- is independent of the particular definition of *W* we pick;

  3- includes only physical states;

  4- states in C_d display ‘classicality’ in a concrete computational sense.

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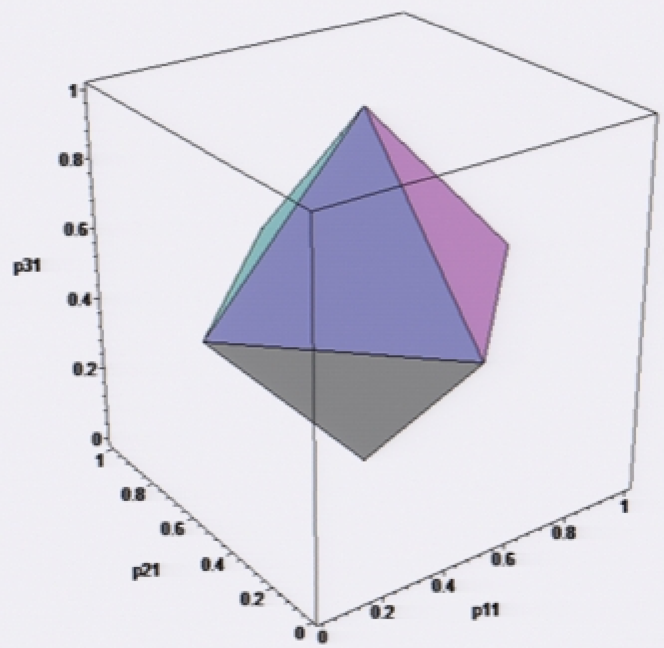
Definition: the set C_d of ‘classical’ states are those with non-negative W in ***all*** definitions of *W* (using a fixed set of MUB’s).

- The set C_2 (one-qubit ‘classical’ states) is the intersection of the two tetrahedra above – an octahedron.



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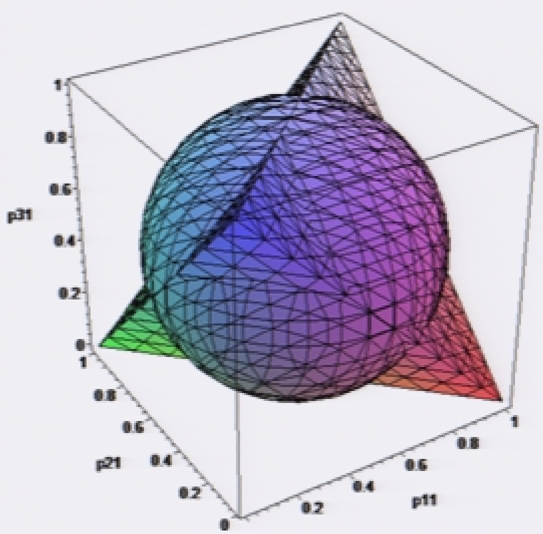

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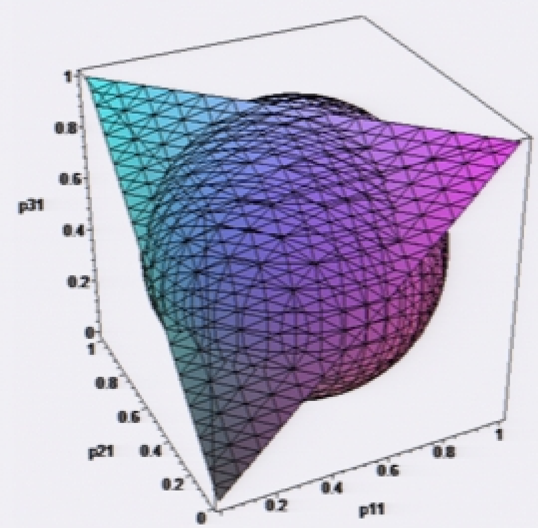

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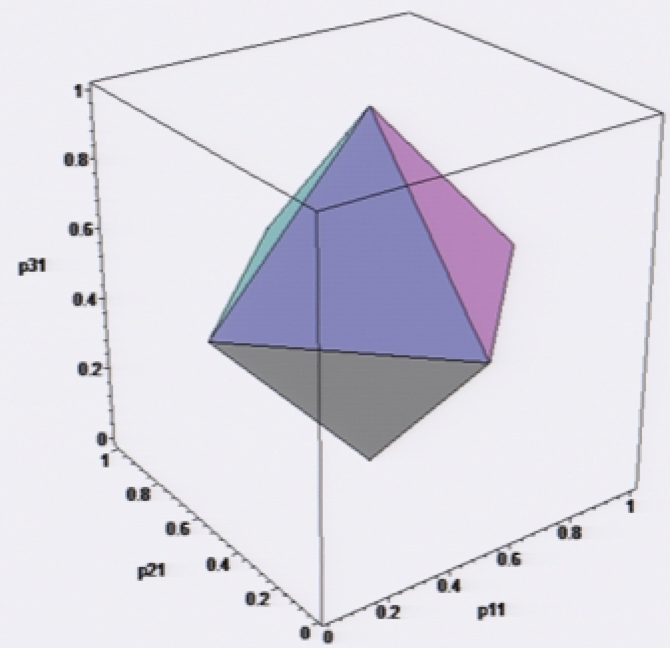


Why do I call states in C_d 'classical'?

d=2 (one qubit case)

- One-qubit ancillas in states in C_2 are *useless* to obtain universal quantum computation in a recent model by Bravyi and Kitaev.

- Bravyi-Kitaev QC Model (quant-ph/0403025):

Perfect operations

- Initialization in $|00\cdots0\rangle$
- Unitaries from the Clifford group (eg. CNOT, H, phase gate)
- Measure single-qubit Paulis.

Imperfect operations

- Preparation of a one-qubit ancilla in a mixed state $\hat{\rho}$

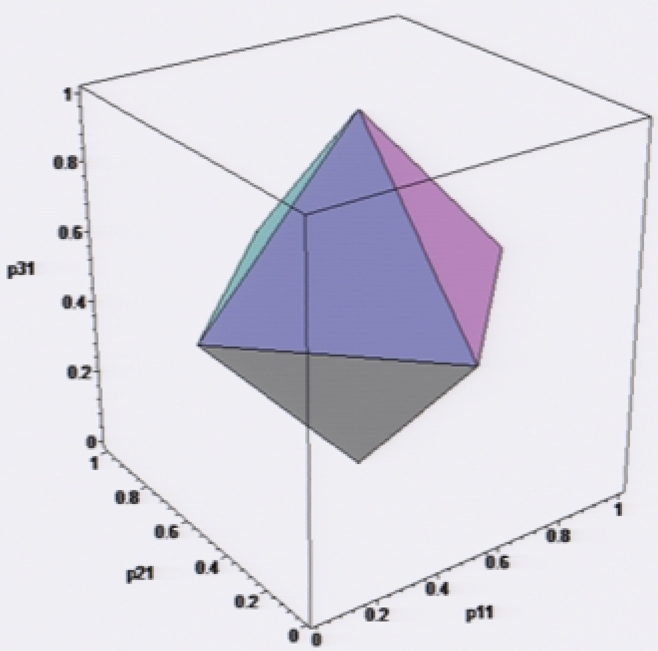
- States in C_2 **fail** to provide for universal quantum computation;
- Bravyi-Kitaev showed that many states outside C_2 are 'non-classical' in the sense of attaining universal quantum computation in this model.

Why do I call states in C_d 'classical'?

general *d* case

- **Theorem**: for any power-of-prime Hilbert space dimension *d*, C_d is the convex hull of the *d*(*d*+1) MUB projectors, i.e.

$$\hat{\rho} \in C_d \Leftrightarrow \hat{\rho} = \sum_{i,j} q_{i,j} |\alpha_{i,j}\rangle\langle\alpha_{i,j}|, \quad \text{with } 0 \le q_{i,j} \le 1 \text{ and } \sum_{i,j} q_{i,j} = 1$$



$$\hat{\rho} \in C_d \Leftrightarrow$$

'shadows' (i.e. measurement outcomes) compatible with classical model in which **only one** MUB has sharp value. Complexity of model (in bits) = $\log_2(d)$

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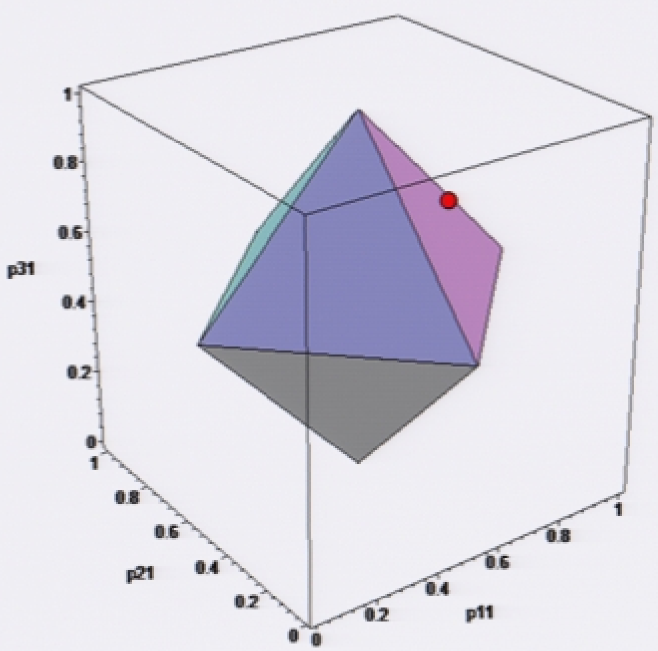

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'shadows' (i.e. measurement outcomes) compatible with classical model in which **only one** MUB has sharp value.

$$\hat{\rho} \text{ has negative } W \Leftrightarrow$$

classical model reconstructed from 'shadows' indicates **there are other states with** sharp values.

Why do I call states in C_d 'classical'?

general *d* case

- Another reason: pure states in C_d have an efficient (size log(*d*)) classical description using the stabilizer formalism.
- How?

Fact: MUB basis vectors can always be chosen to be stabilizer states (eigenstates of generalized Pauli operators)

- Example: 5 MUB's for 2 qubits can be defined as joint eigenstates of Paulis in each line. Efficient description: generators of the subgroup {each line, identity}, and their eigenvalues.

MUB 1	σ_z^1	σ_z^2	$\sigma_z^1\sigma_z^2$
MUB 2	σ_x^1	σ_x^2	$\sigma_x^1\sigma_x^2$
MUB 3	σ_y^1	σ_y^2	$\sigma_y^1\sigma_y^2$
MUB 4	$\sigma_x^1\sigma_z^2$	$\sigma_y^1\sigma_x^2$	$\sigma_z^1\sigma_y^2$
MUB 5	$\sigma_x^1\sigma_y^2$	$\sigma_y^1\sigma_z^2$	$\sigma_z^1\sigma_x^2$

$\Rightarrow$

Negativity of *W* is required for pure-state universal quantum computing…

Open problems

- Apply insights from the discrete case to the continuous Wigner function W(q,p), and other quasi-probability distributions. In what computational sense are non-negative W(q,p) `classical'?

- Characterize unitaries (and general operations) which keep *W* non-negative.

- Visualize quantum computing algorithms (cf. Bianutti *et al.*, Miquel *et al.*, Paz) and other quantum information protocols.

Conclusions

- I characterized the set C_d of states with non-negative discrete Wigner function W in **all** definitions of W. The set C_d is the convex hull of a set of stabilizer states.

- States in C_d are `classical' in many senses:

  – they can be described with non-negative quasi-probability distributions;
  – they have an efficient (size log(d)) classical description;
  – one-qubit states outside of C_2 are necessary for universal quantum computation in the Bravyi-Kitaev model;
  – *d*-dimensional states outside of C_d are necessary for pure-state universal quantum computation.

References:

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- defining discrete Wigner functions: K. S. Gibbons, M. J. Hoffman, W. K. Wootters, quant-ph/0401155.
- mutually unbiased bases: Wootters and Fields, Ann. Phys. (N.Y.) 191(2), 363 (1989); Bandyopadhyay *et al*., quant-ph/0103162; Lawrence *et al.* PRA 65, 032320 (2002); Pittenger and Rubin, quant-ph/0308142; Klappenecker and Roetteler, quant-ph/0309121.
- one-qubit non-classical states as a resource : Bravyi and Kitaev, quant-ph/0403025.
- visualizing quantum computing with discrete Wigner functions: Bianucci et al., quant-ph/0106091; Miquel et al., Nature 418, 59 (2002); Paz, PRA 65, 062311 (2002).

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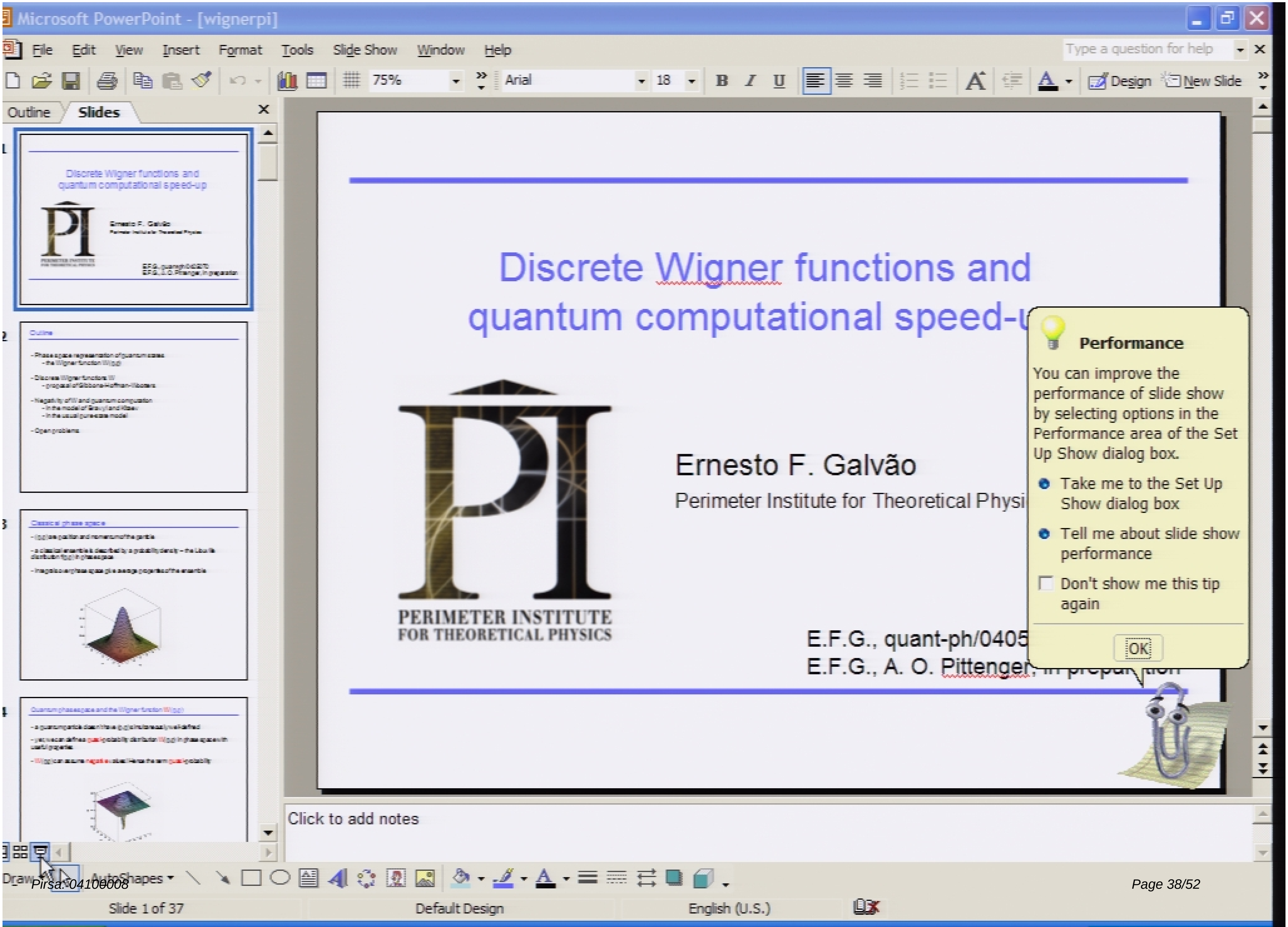

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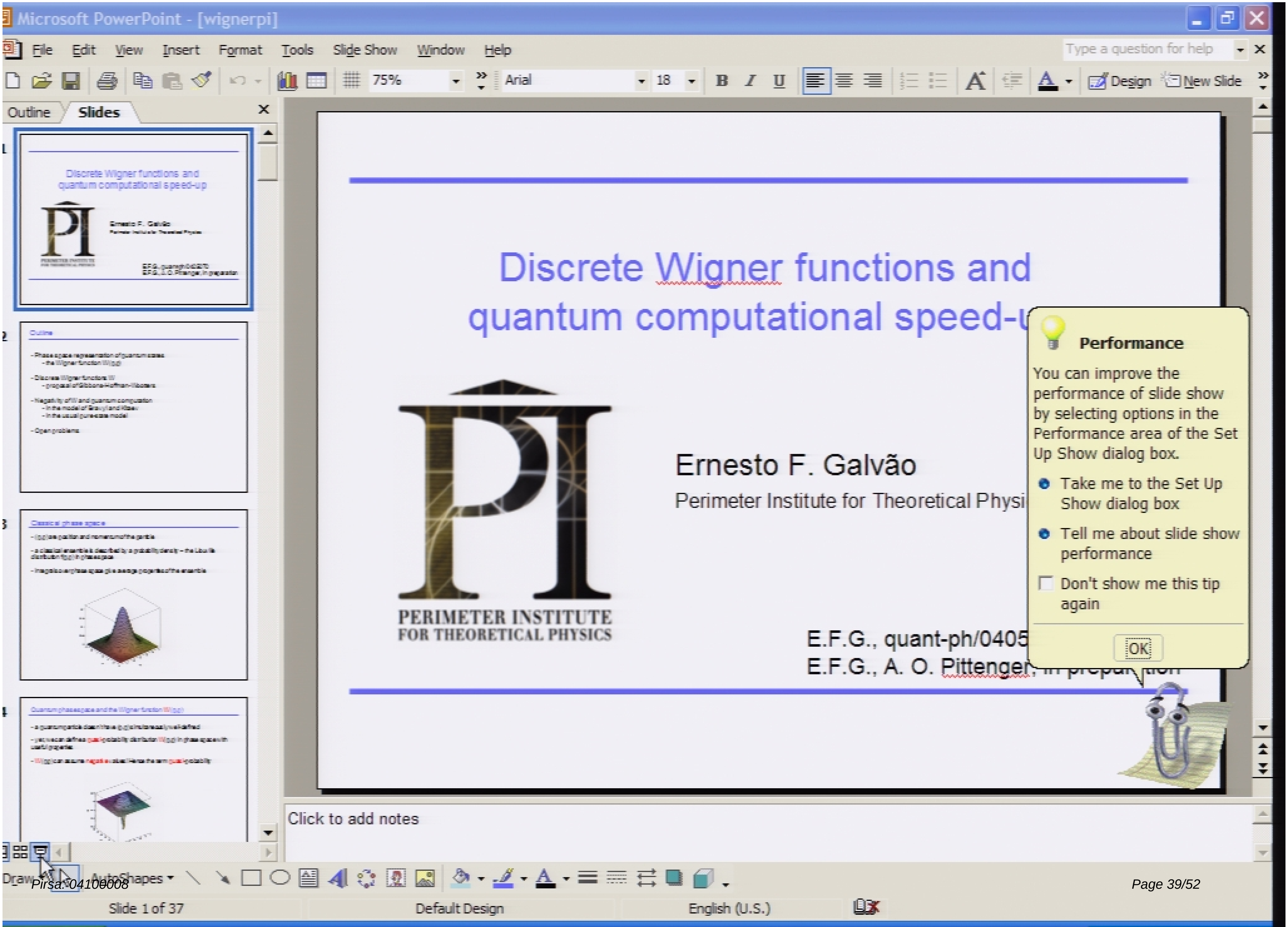
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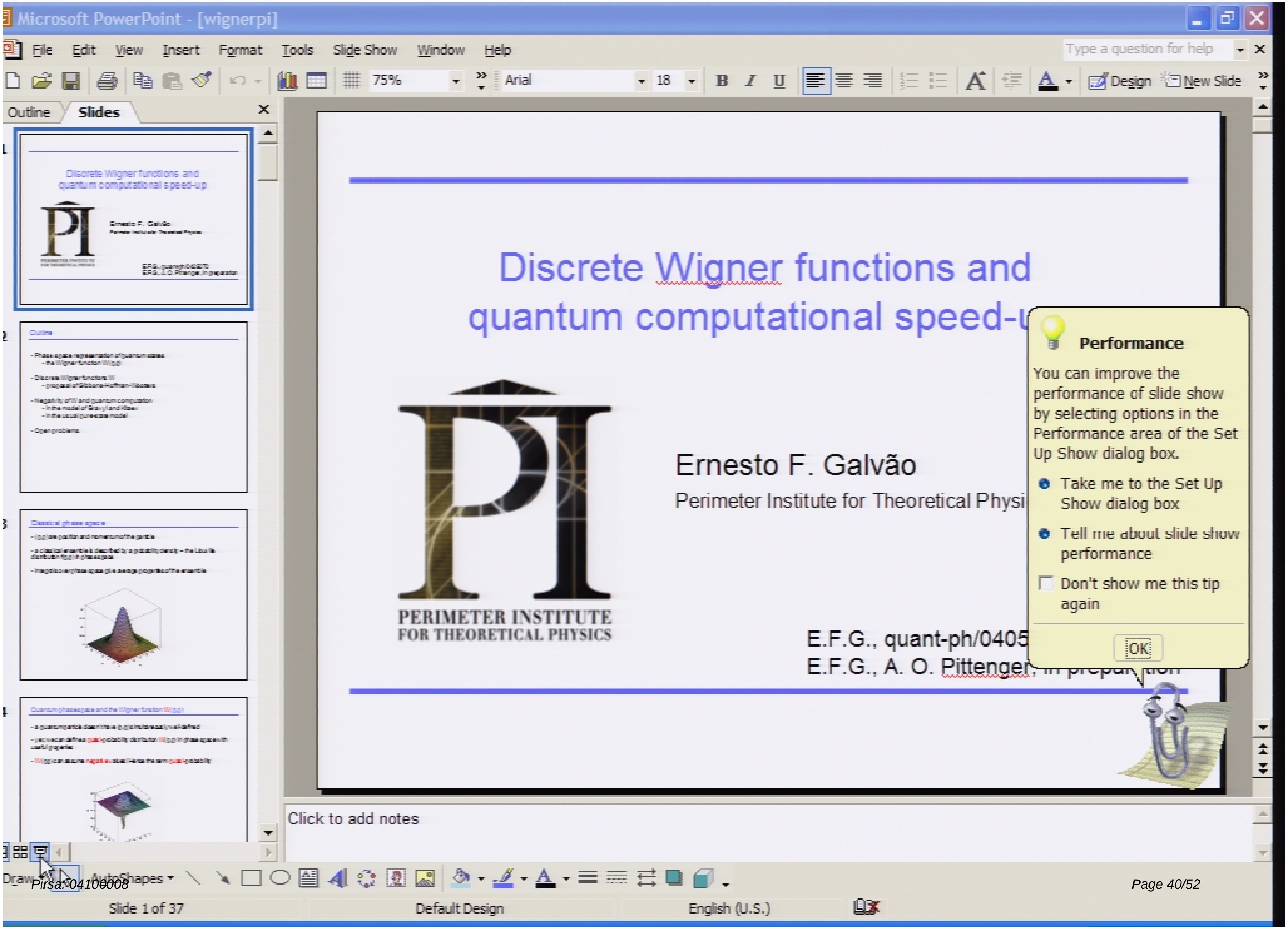
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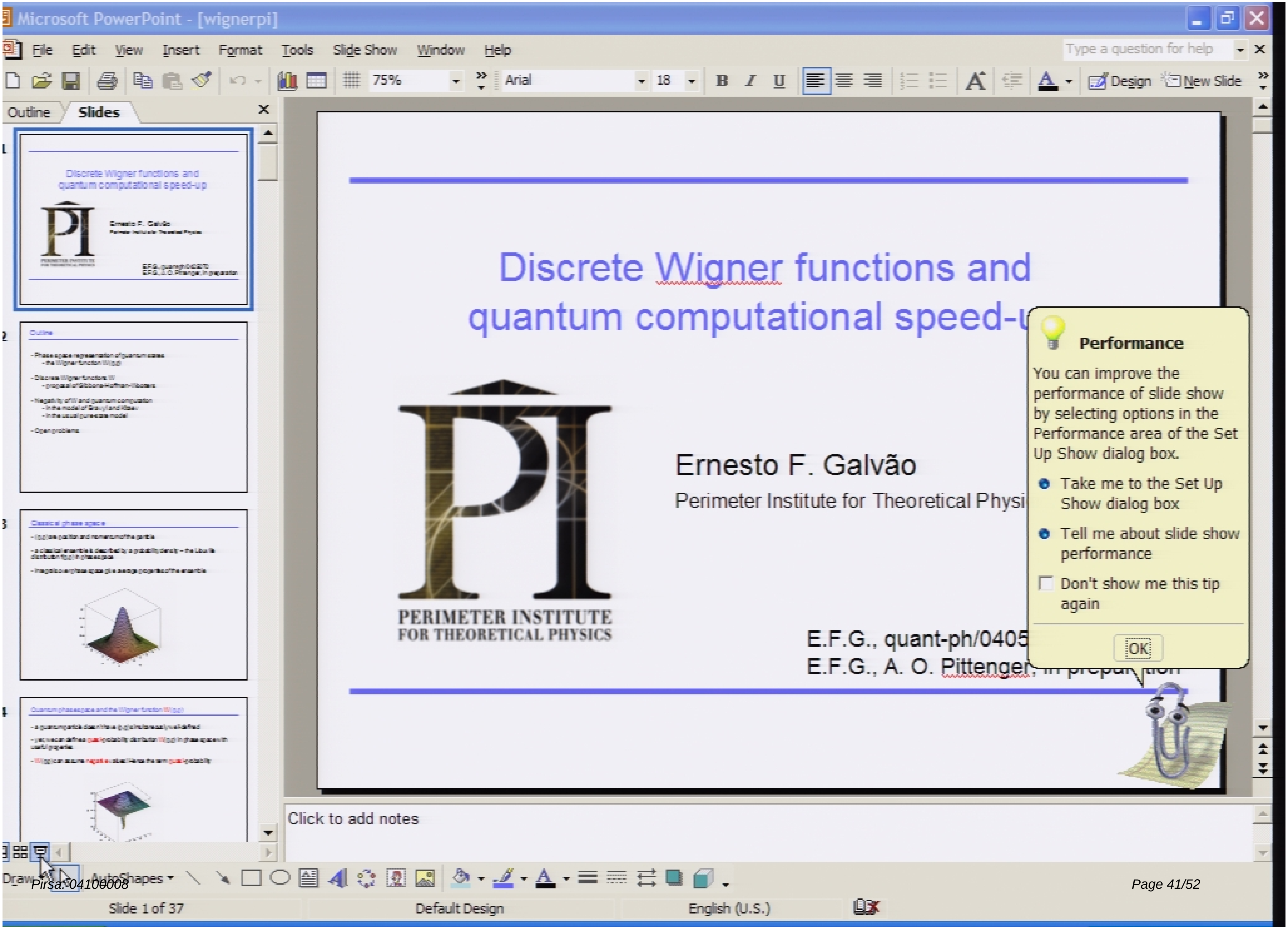
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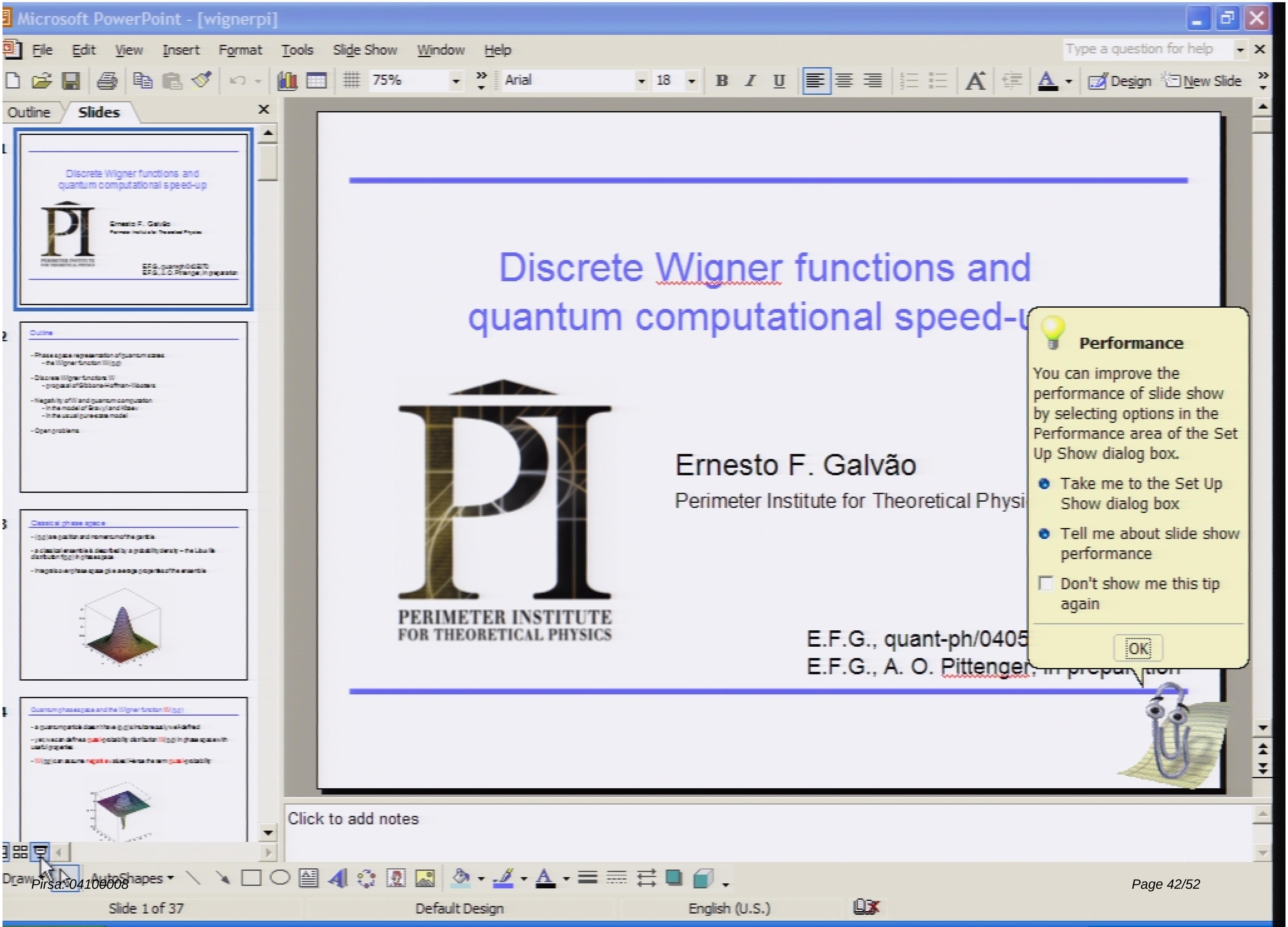
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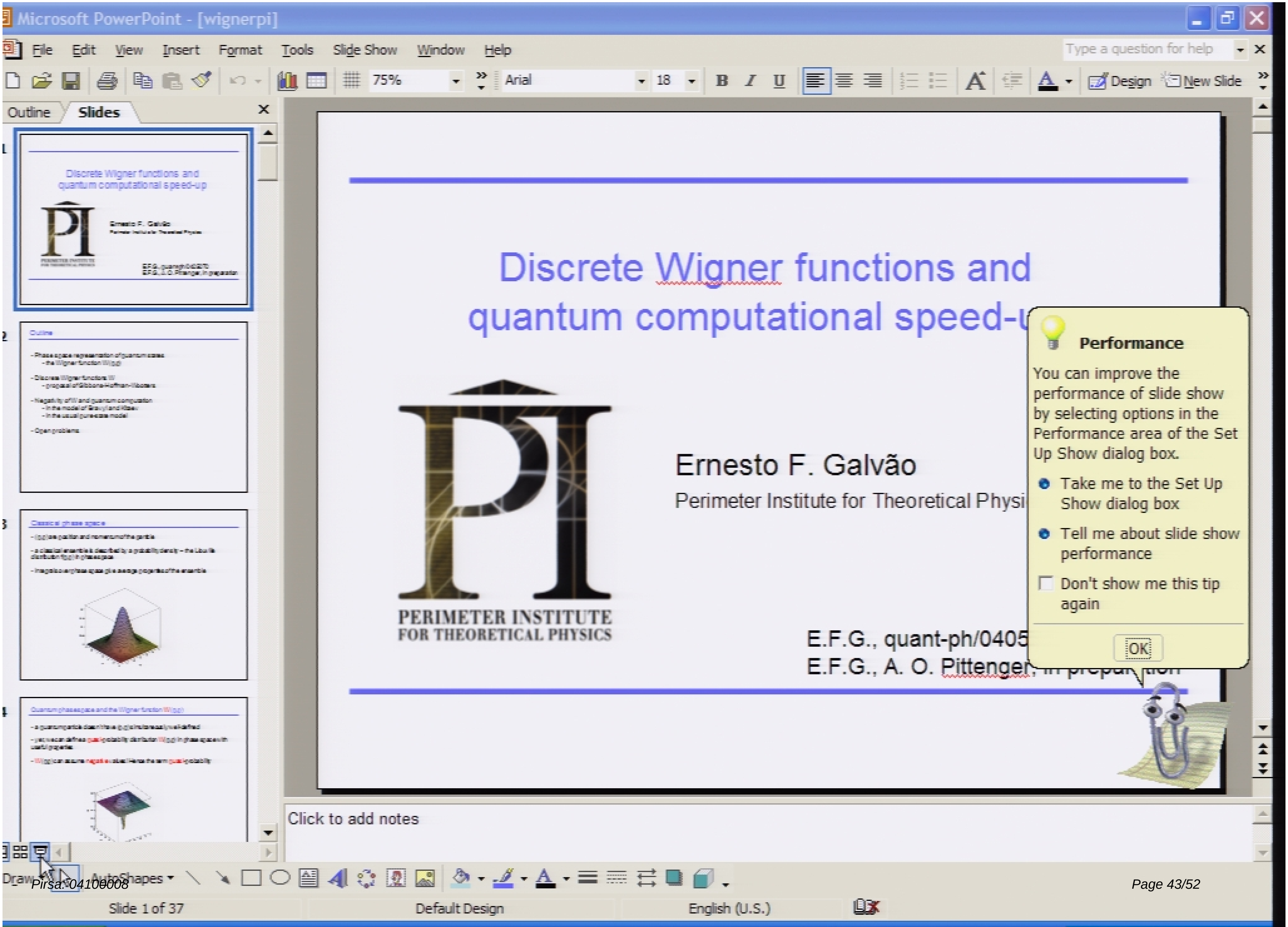
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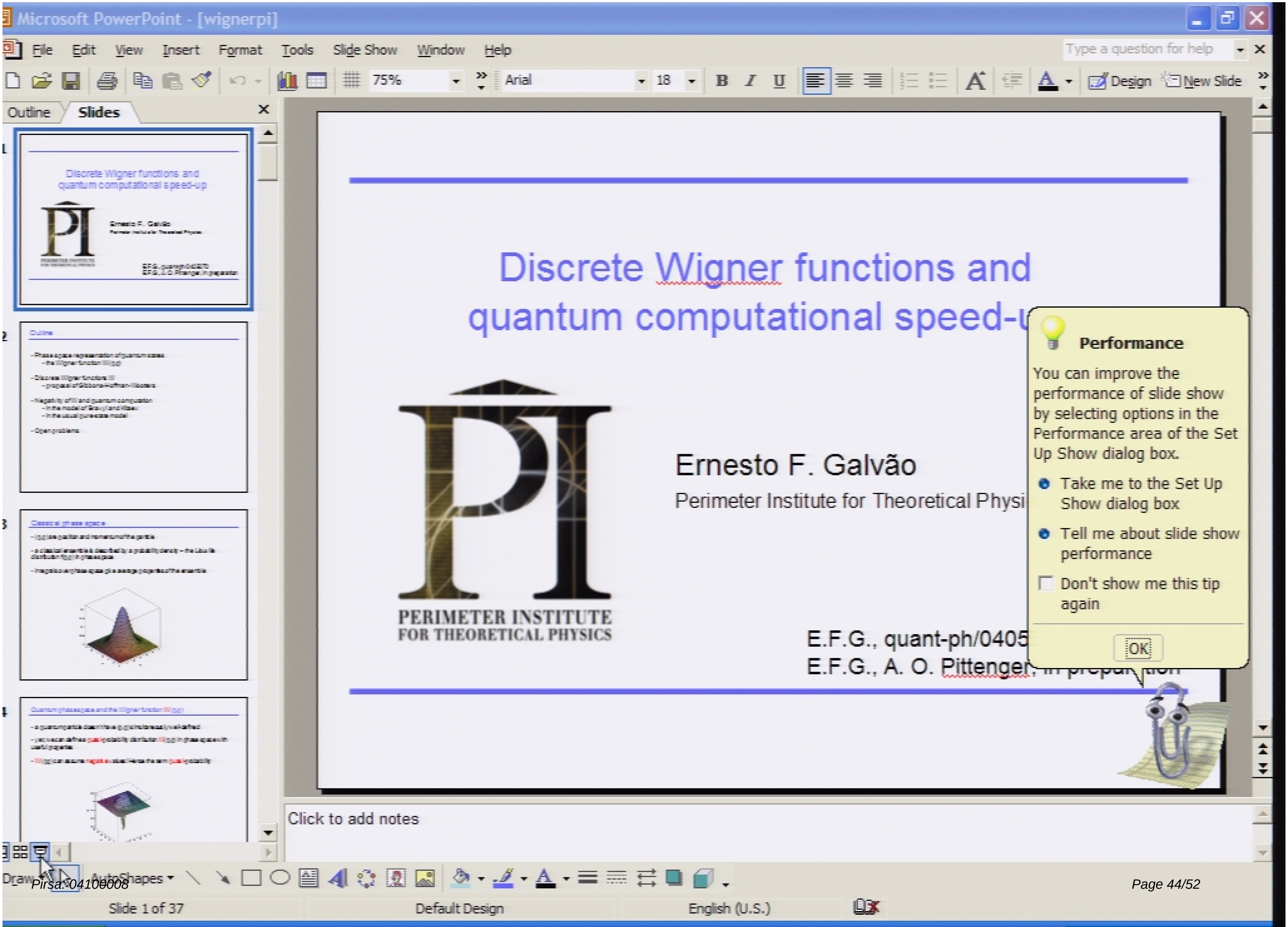
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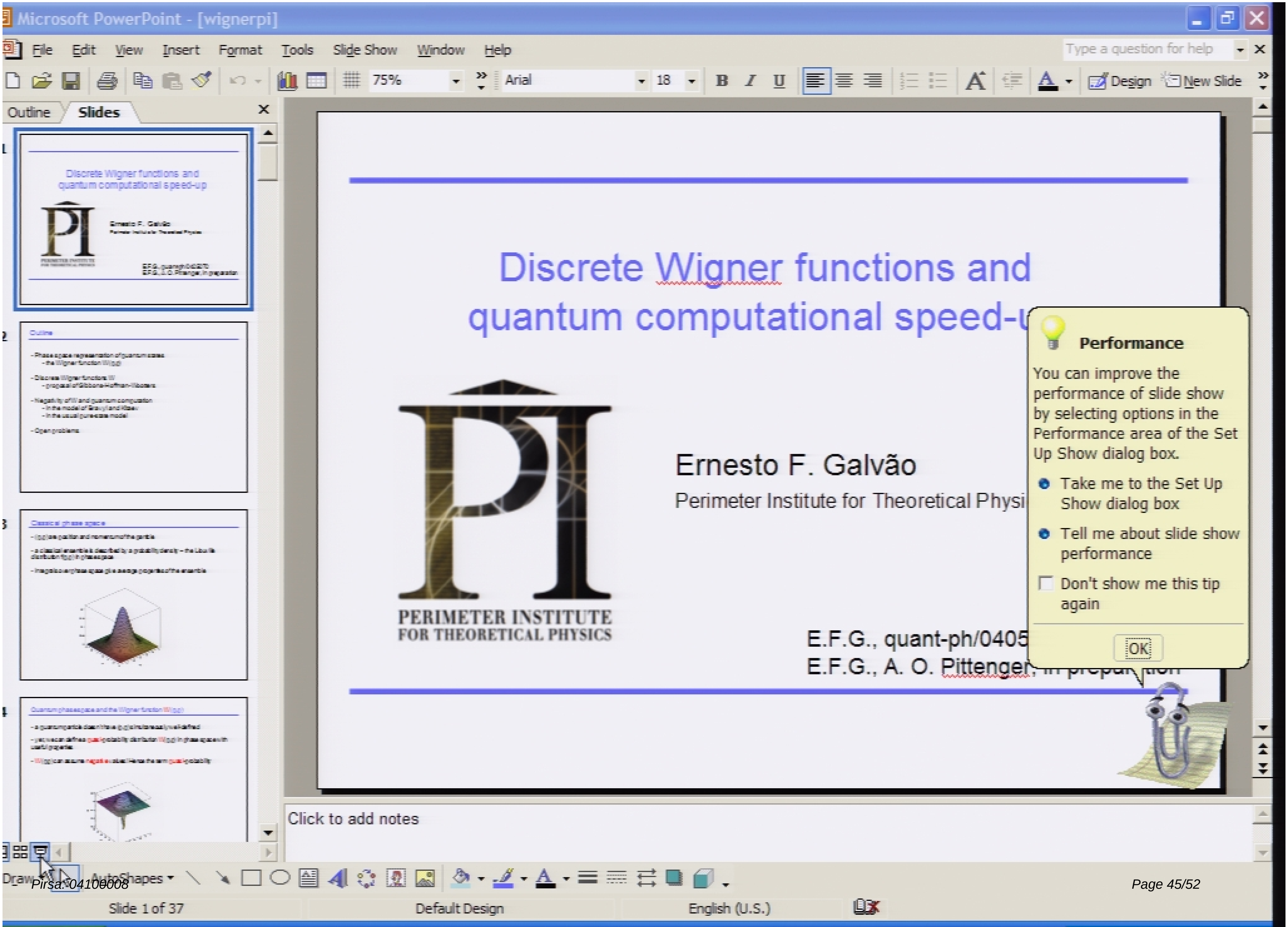
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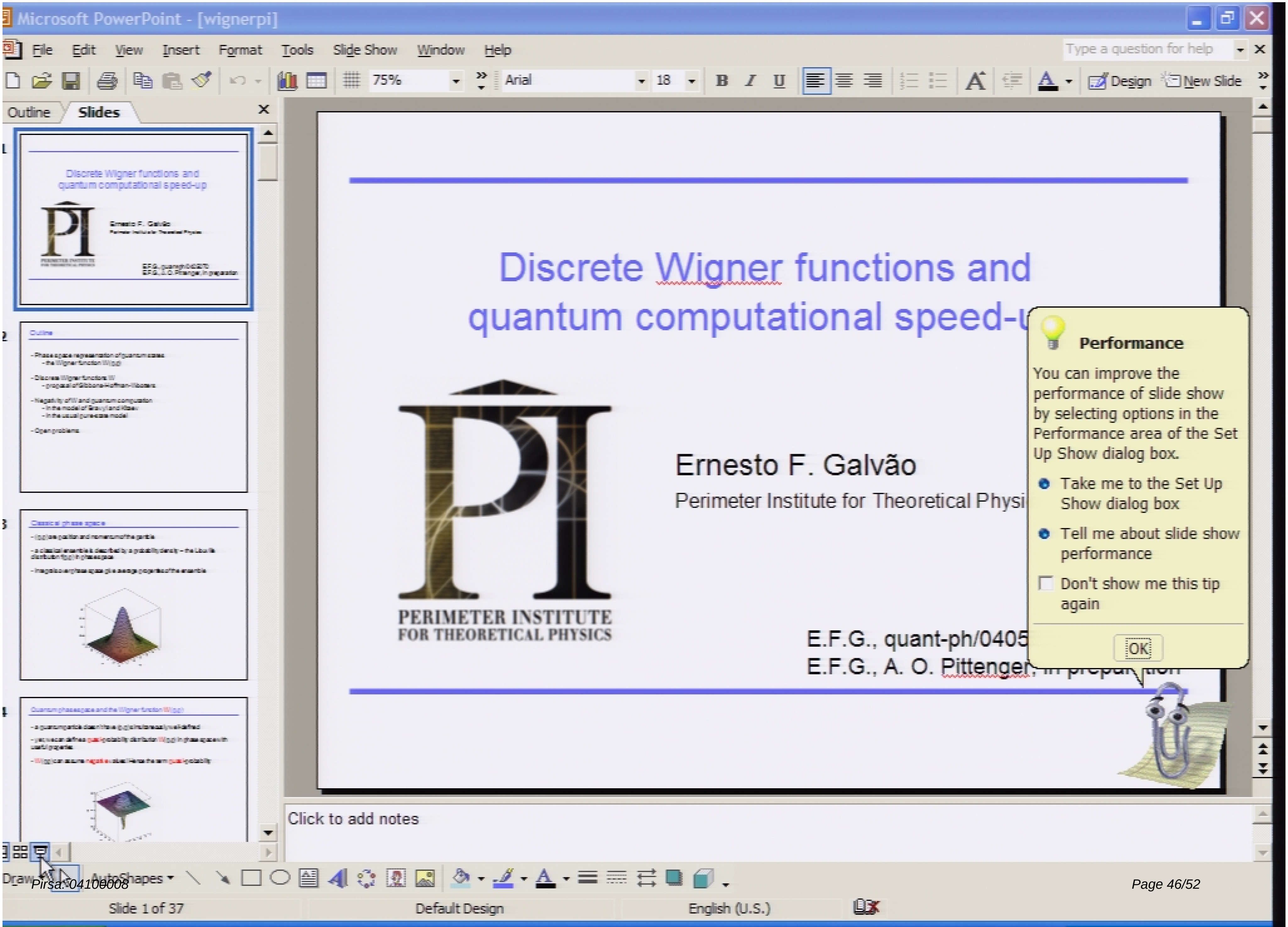
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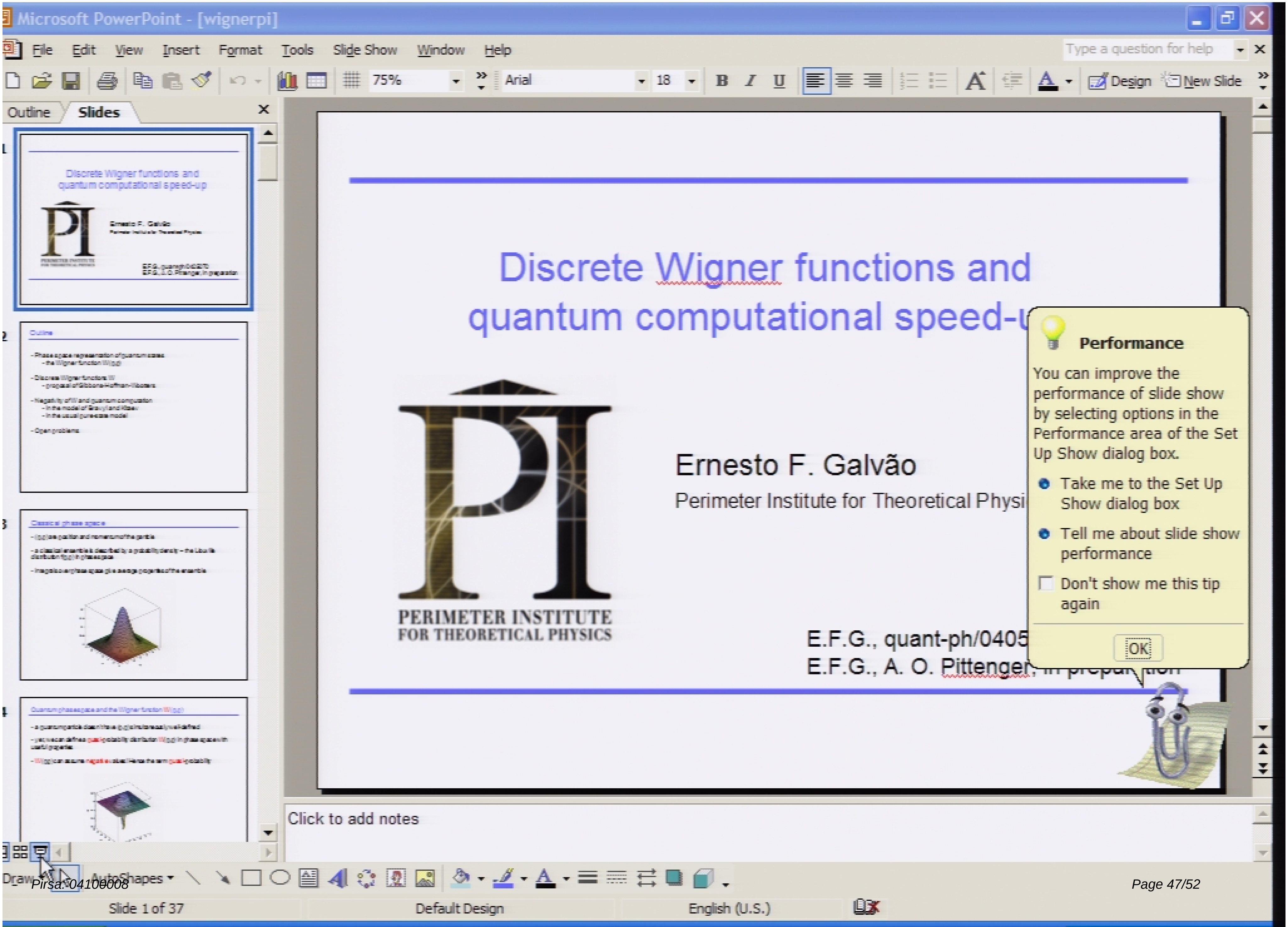
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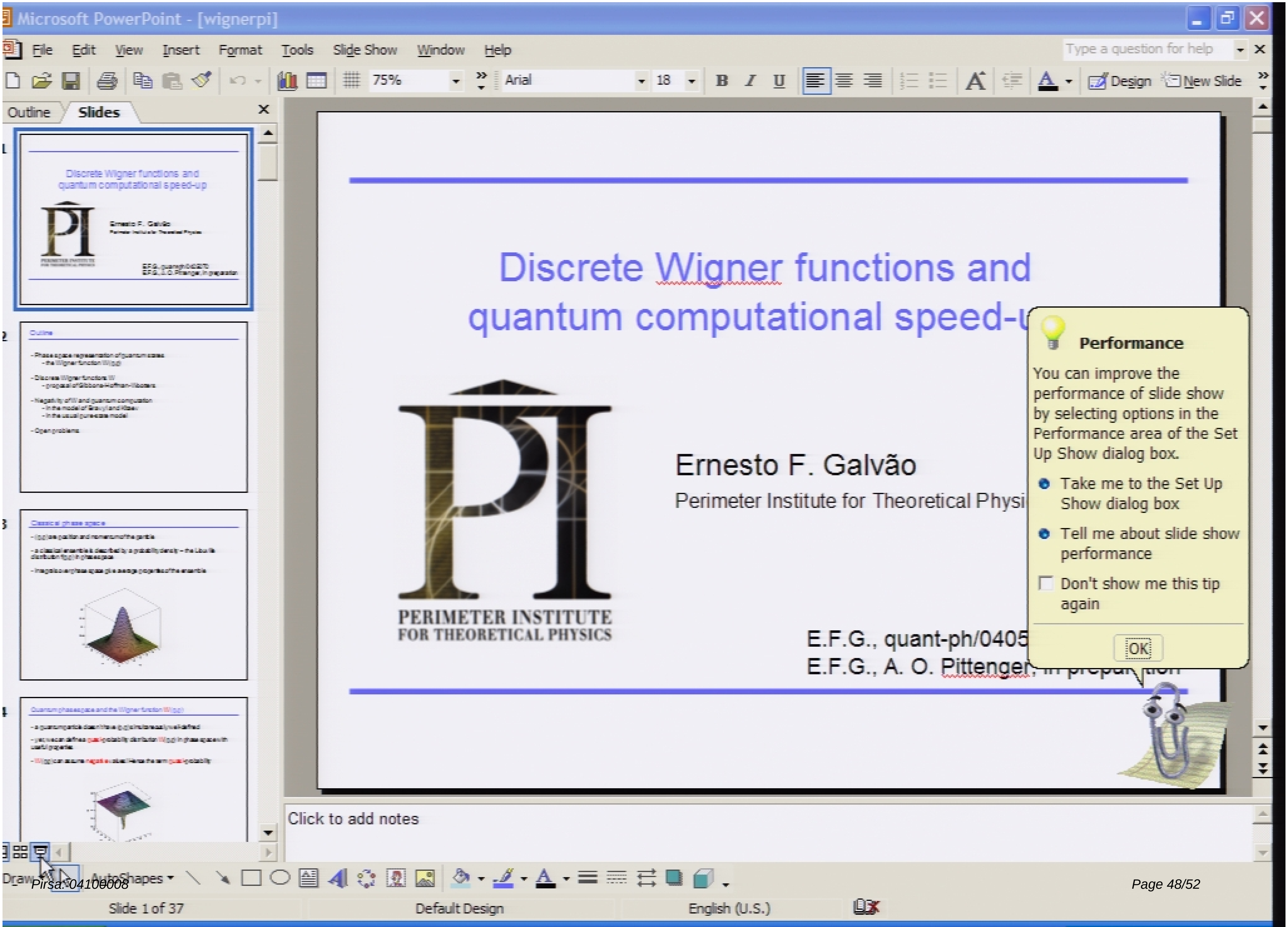
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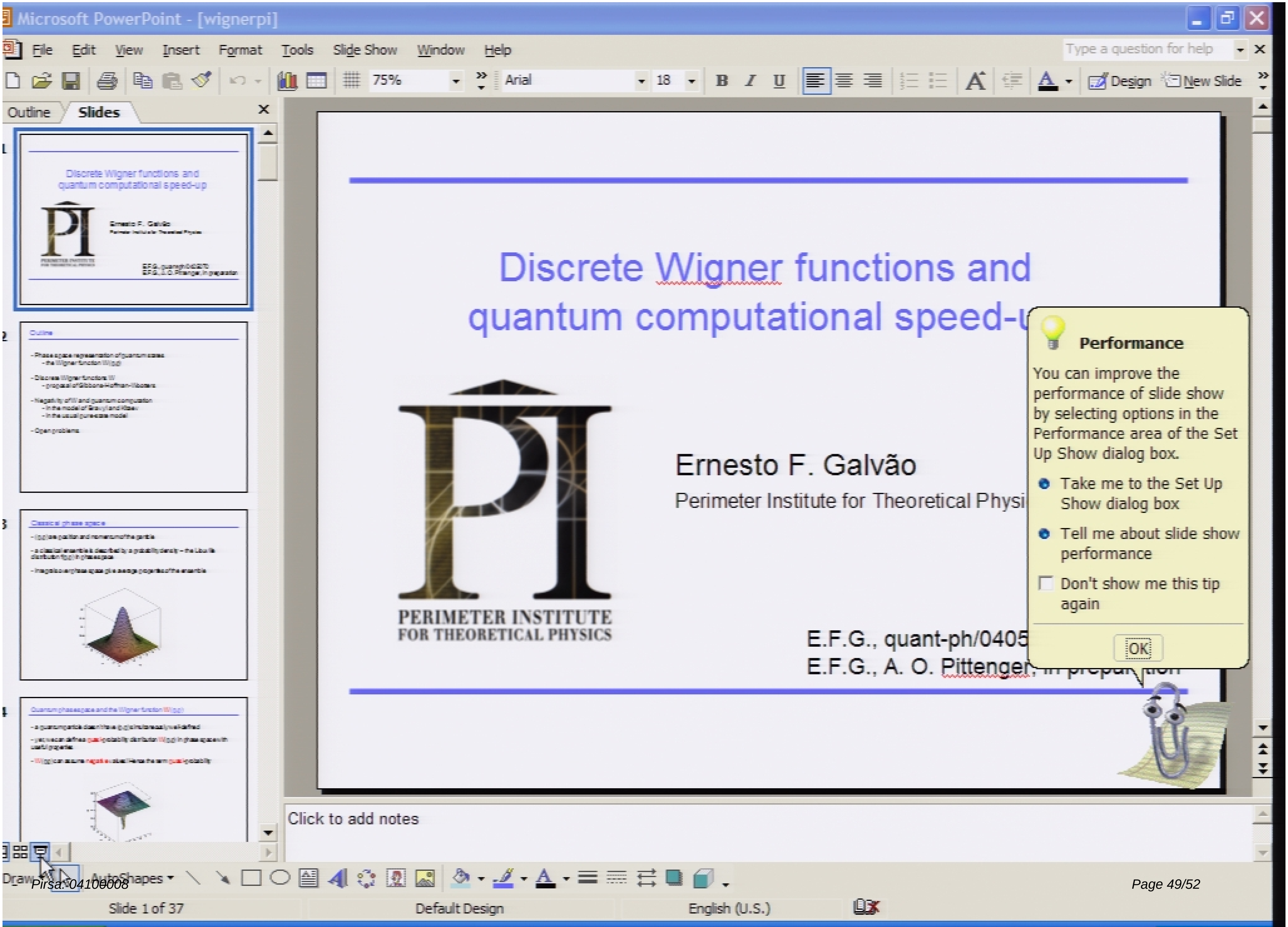
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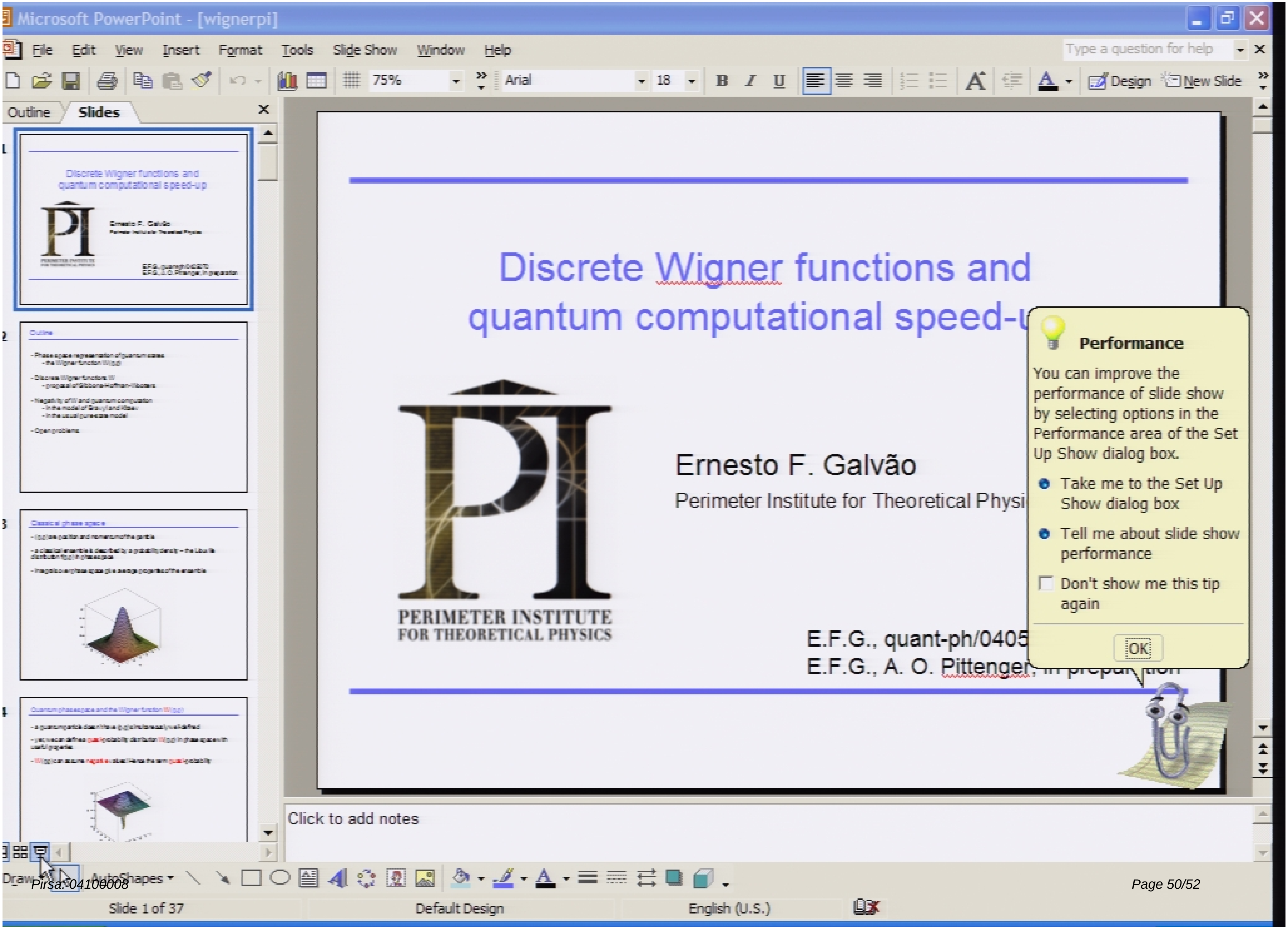
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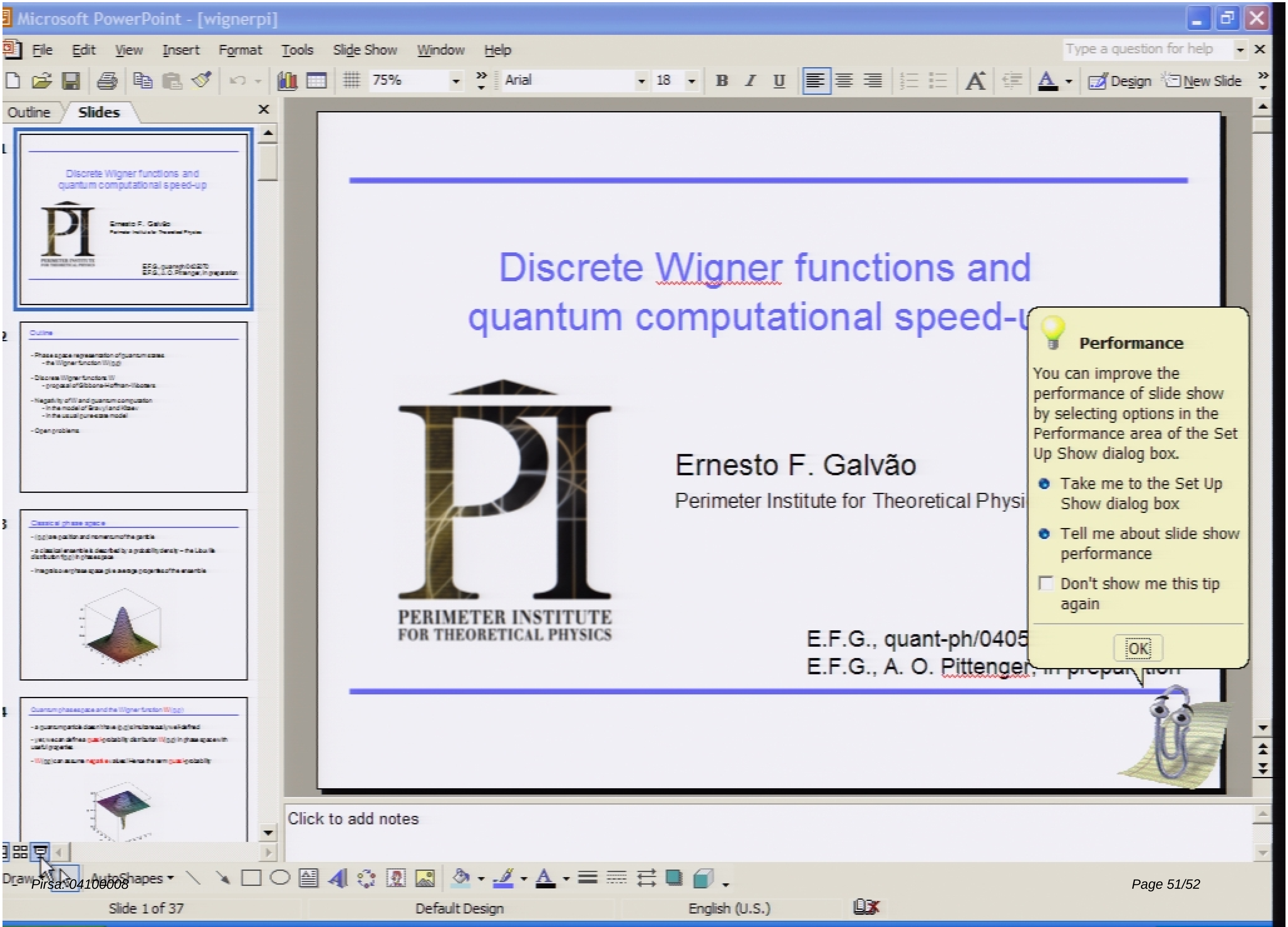
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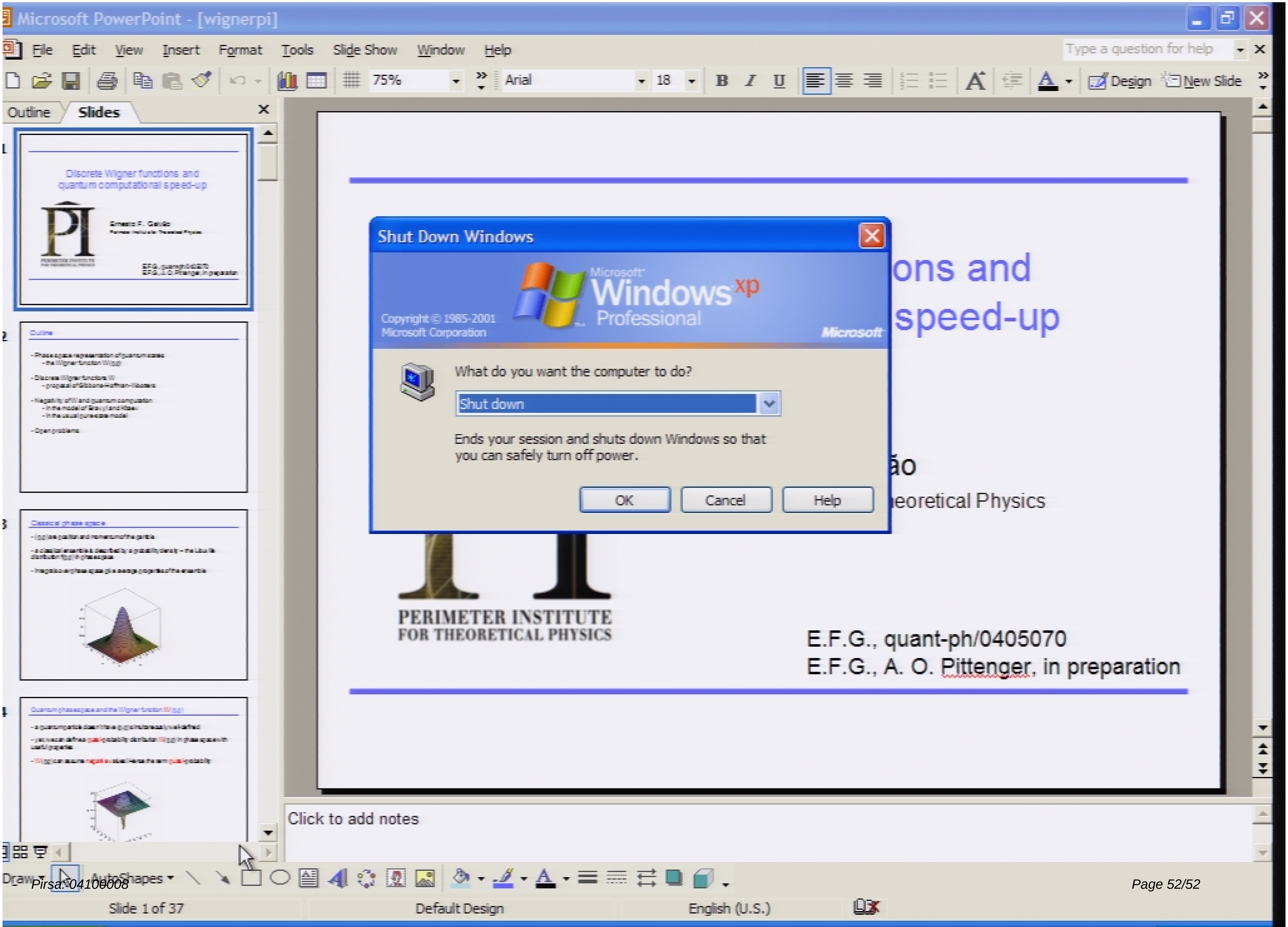
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