Title: What the H&$! is Quantum Information Science?

Date: Jul 29, 2008 09:00 AM

URL: http://pirsa.org/08070044

Abstract:

What the H&$! is Quantum Information Science?

Robin Blume-Kohout

What Information Theory Does

Communication Theory

Communication Theory

- Lets us lock on to GPS satellites.

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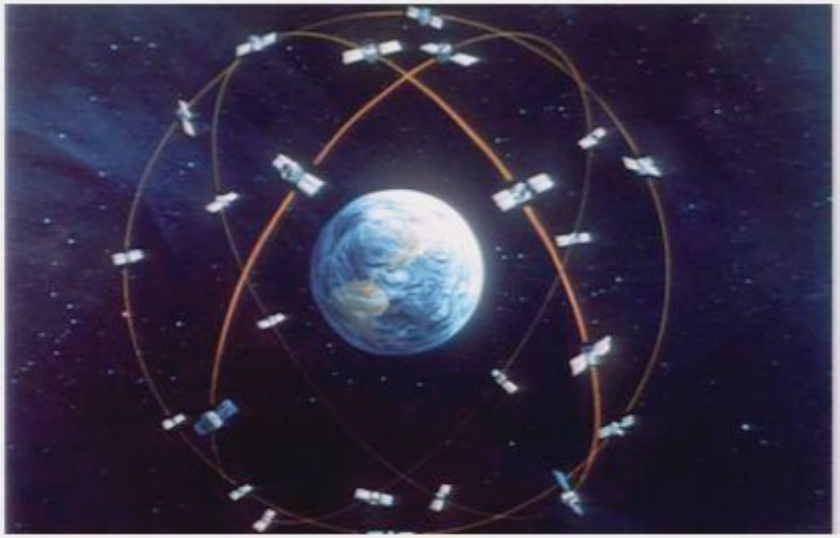
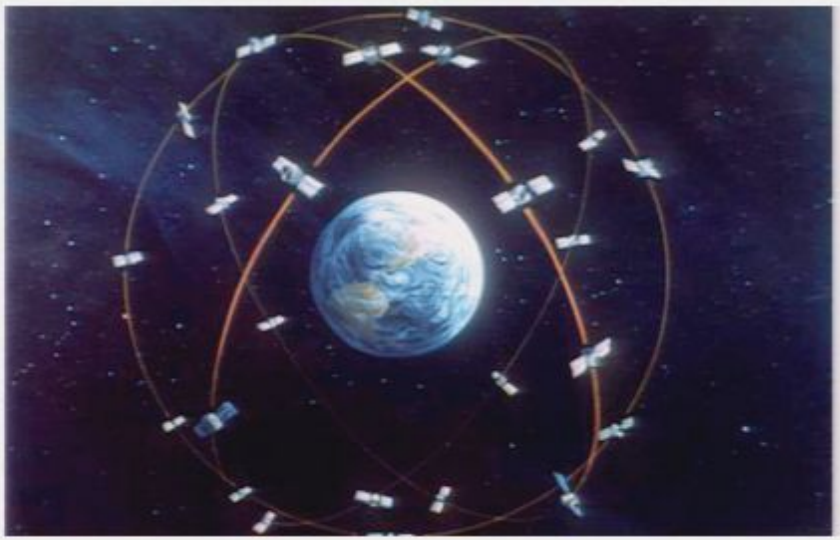


Communication Theory



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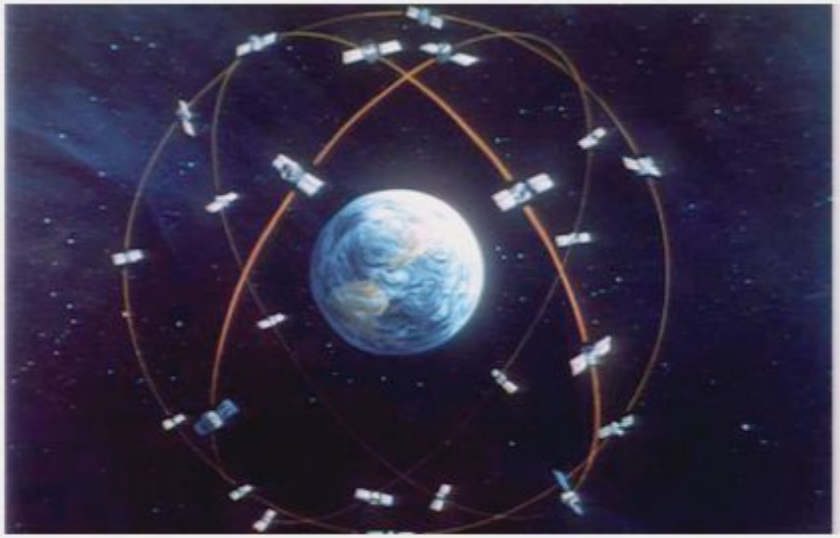

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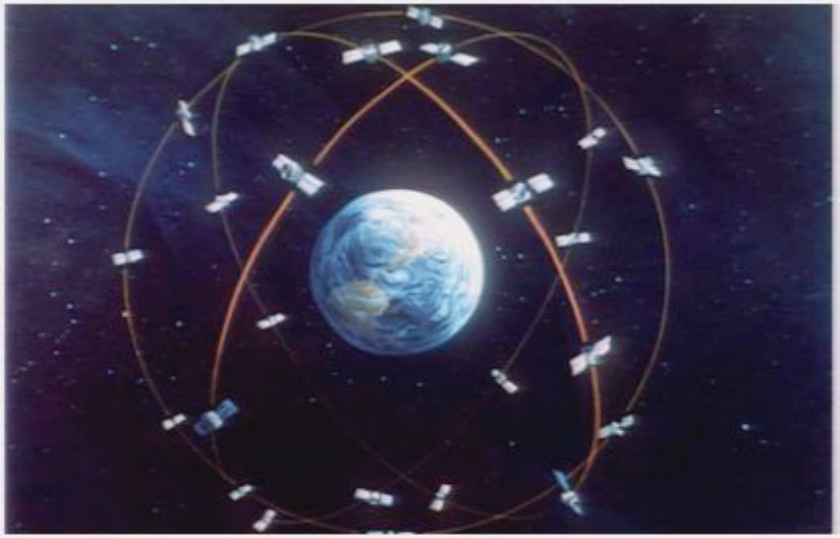
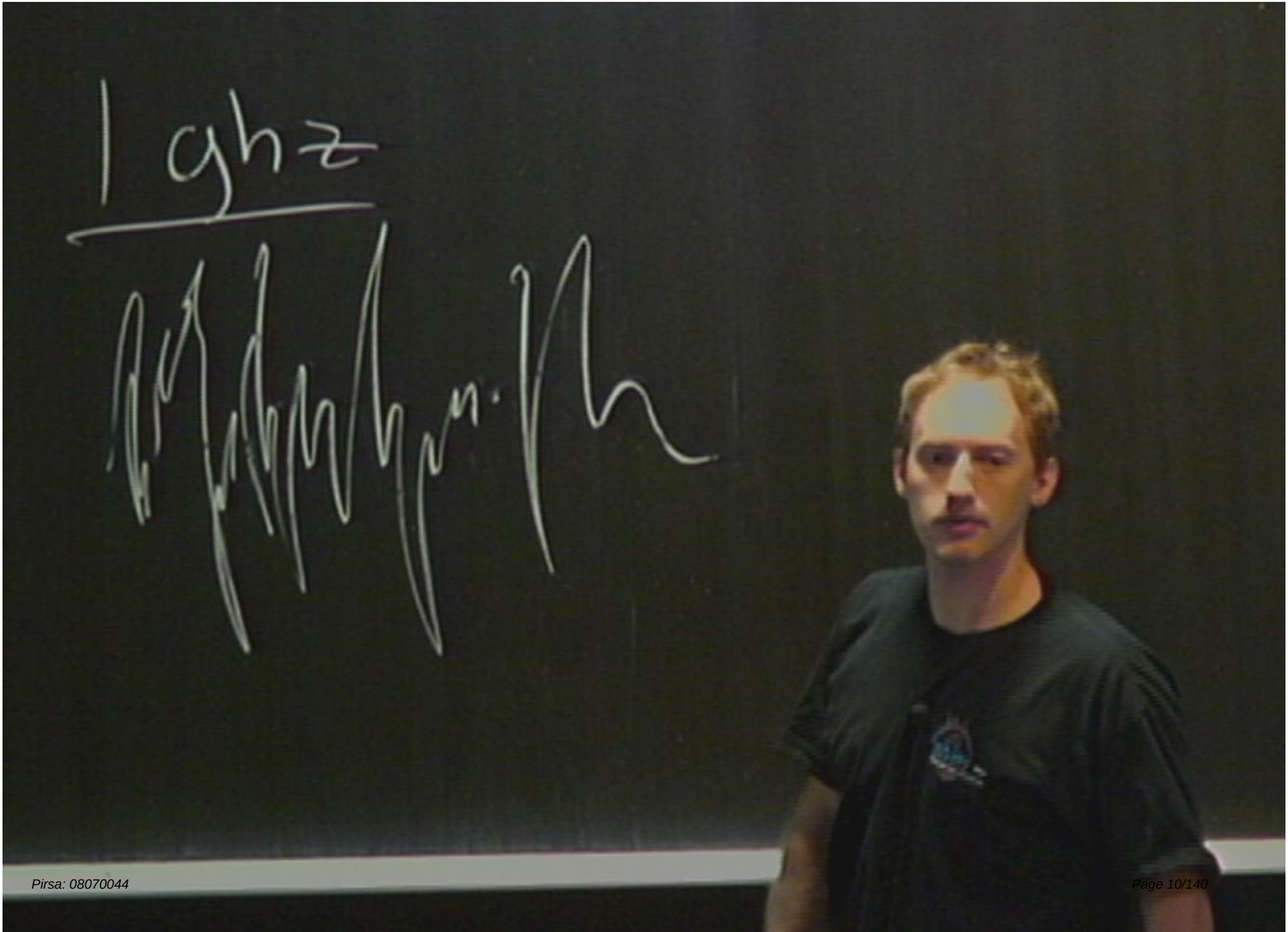
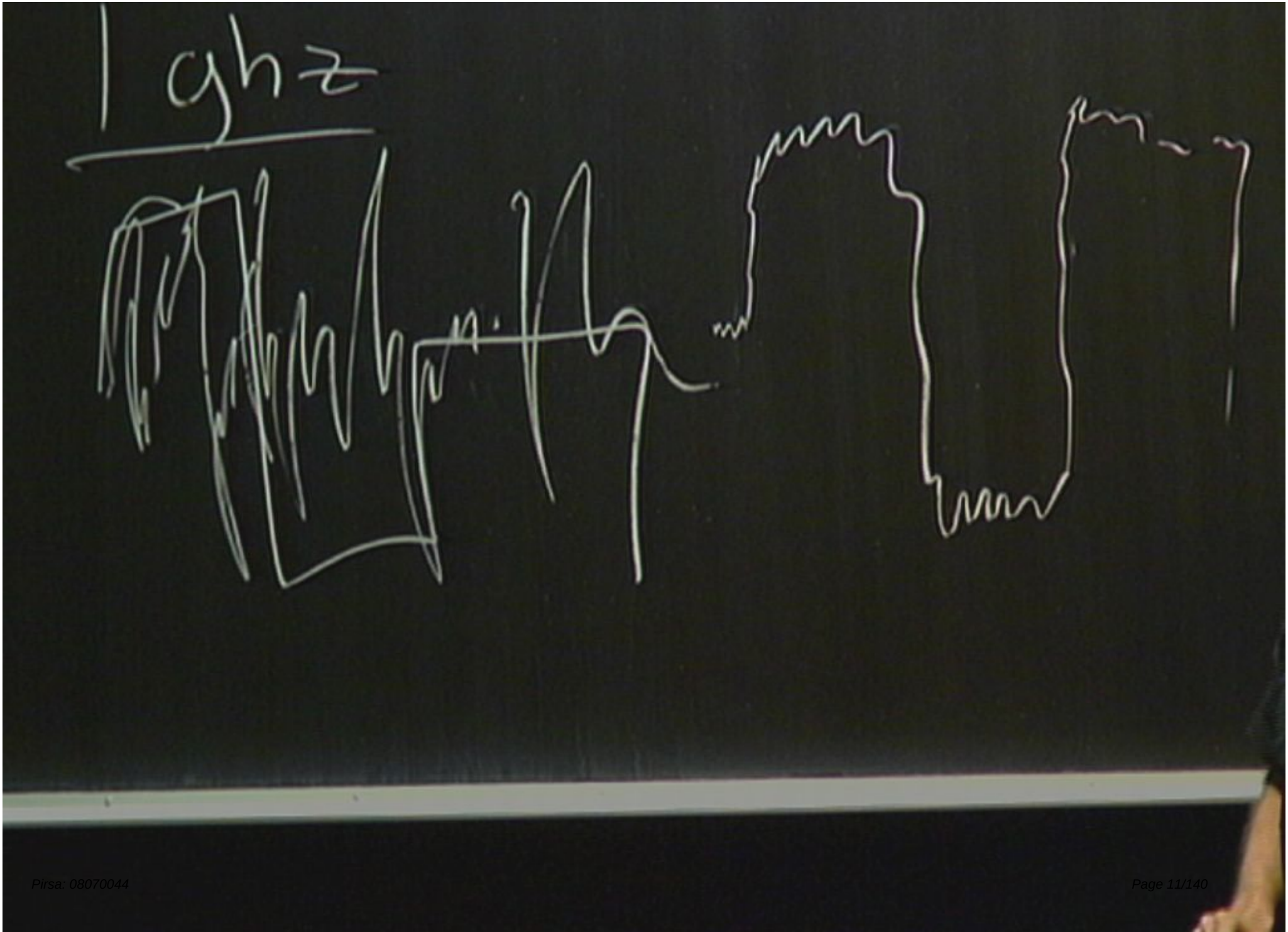


- Lets us lock on to GPS satellites.
- How to communicate despite noise
  - *transmitting information through noisy channels*


1 ghz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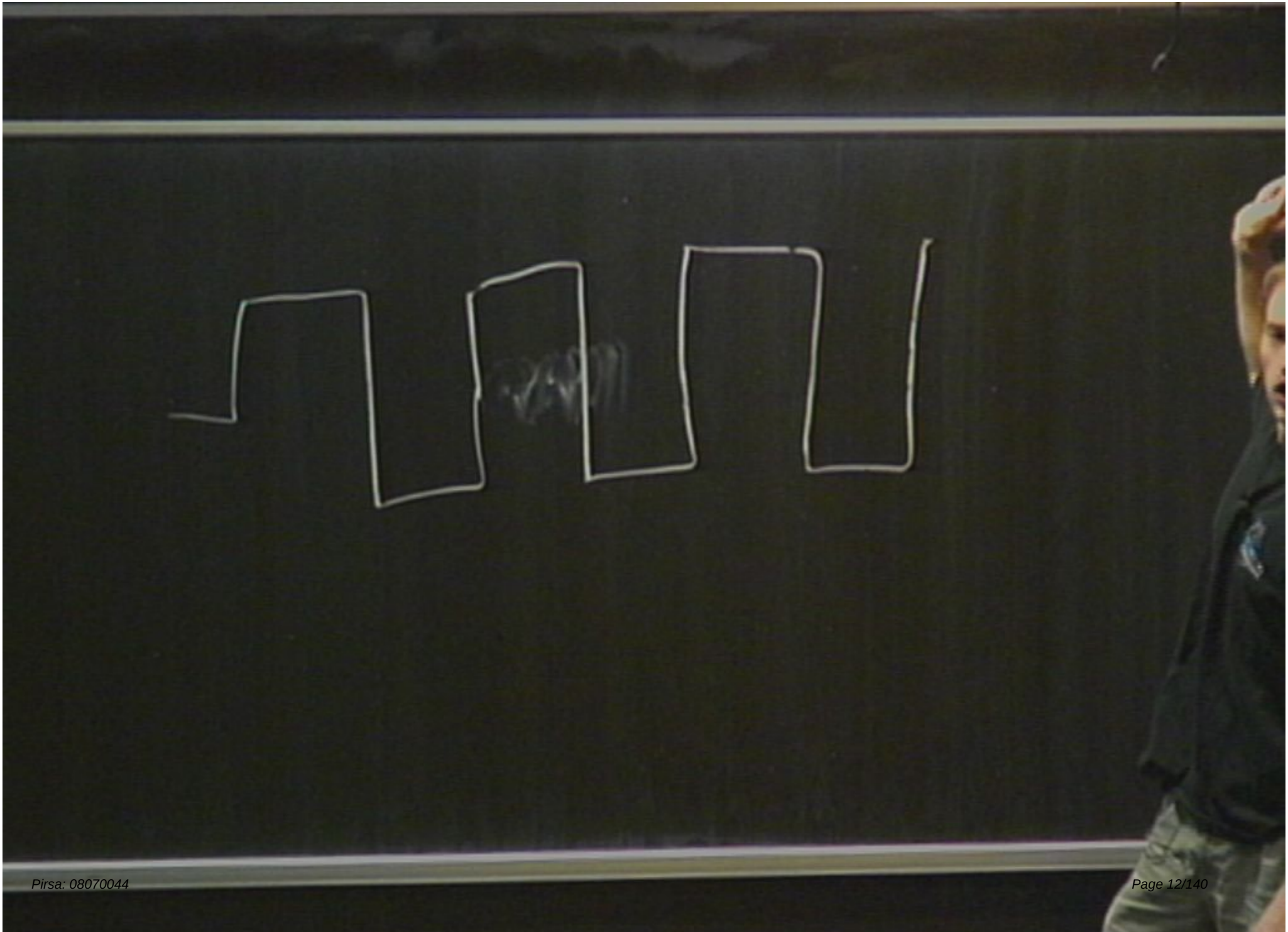
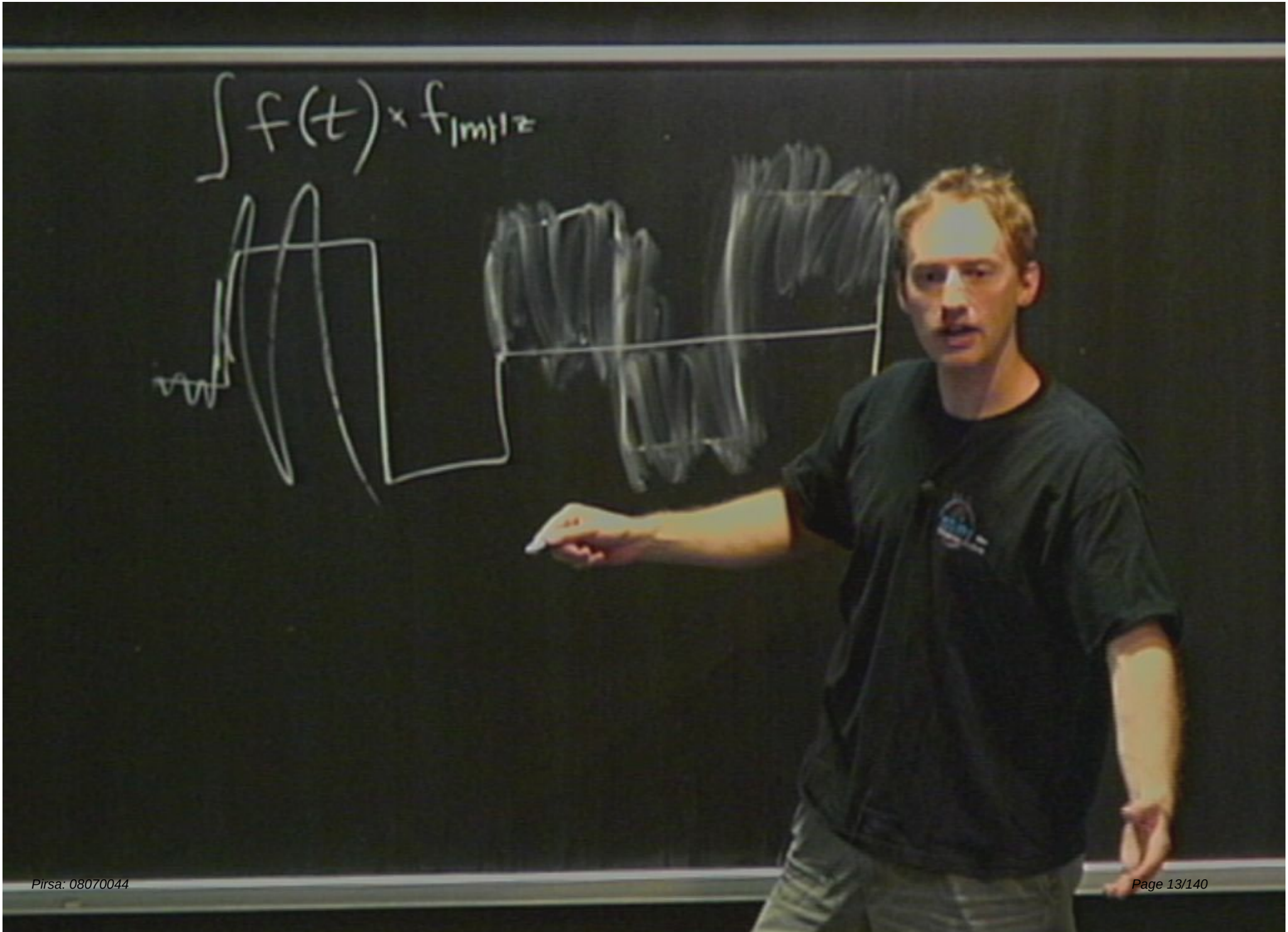
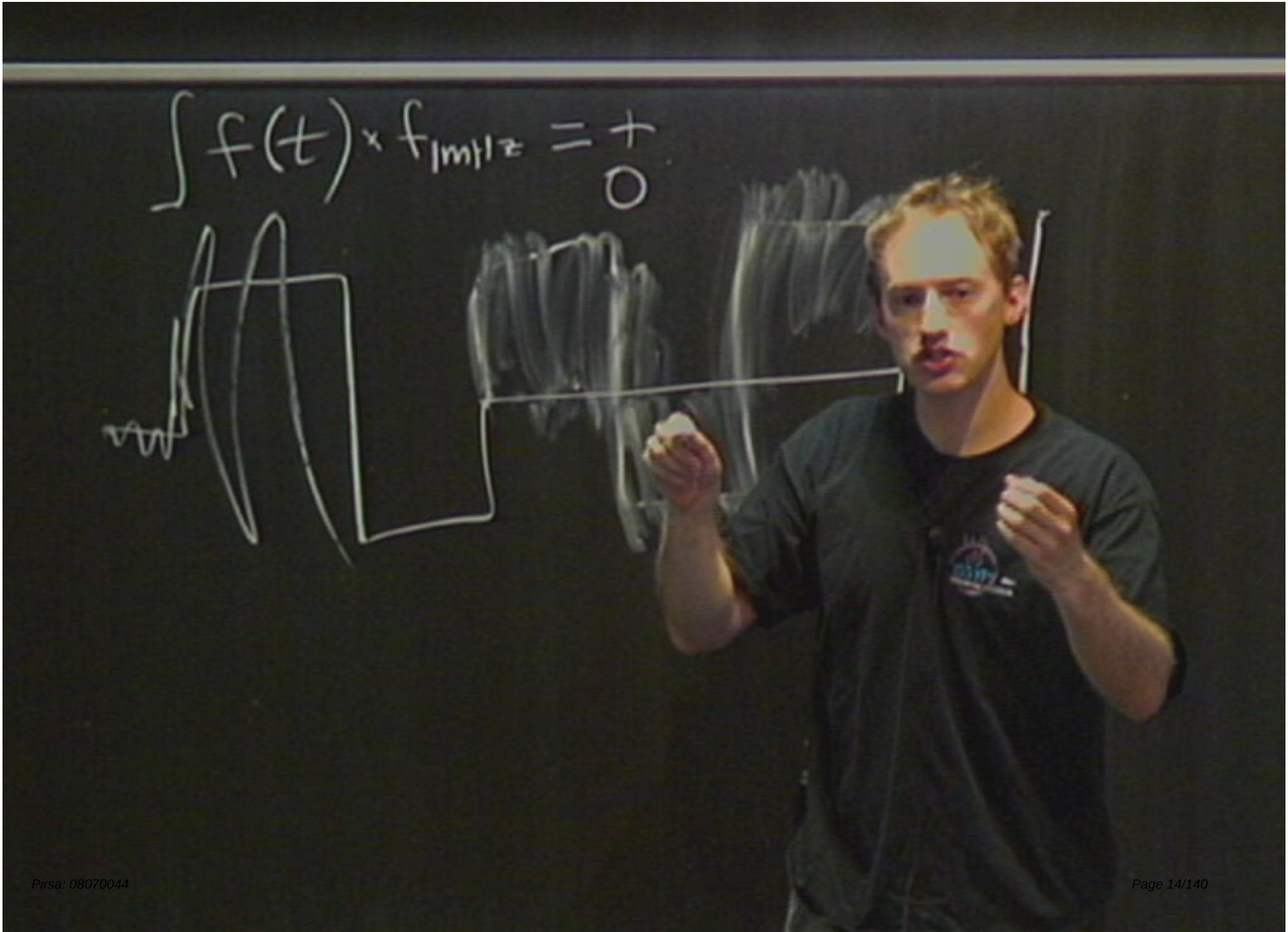
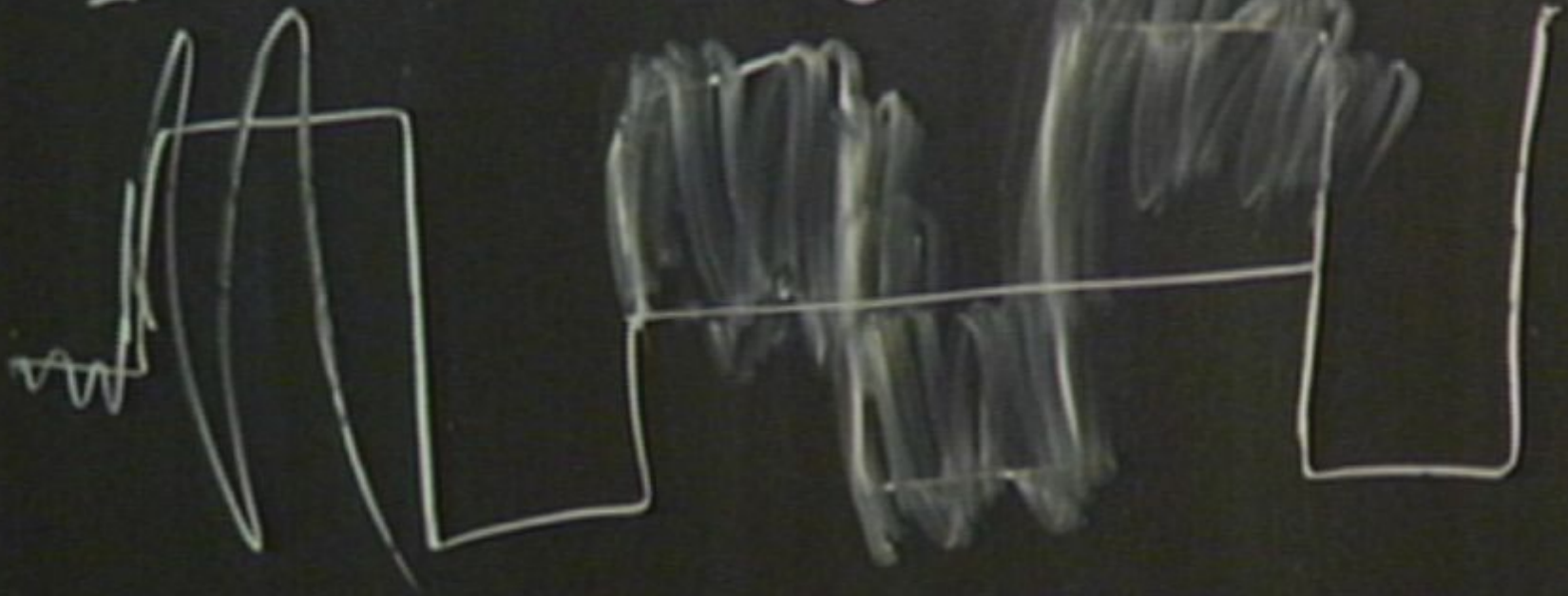


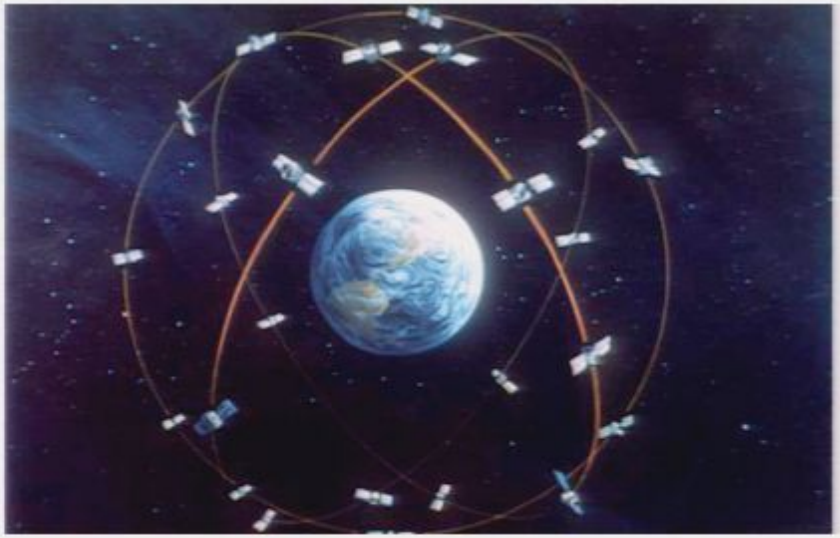

∫ f(t) × f


$\int f(t) \times f_{\text{impulse}} = ?$

$$\int f(t) \times f_{\text{impulse}} = \begin{matrix} + \\ 0 \end{matrix}$$



Communication Theory



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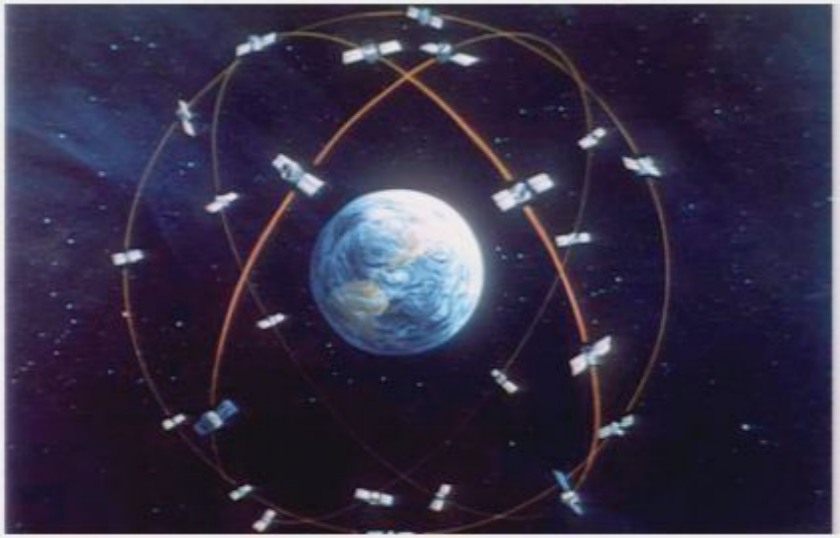

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- E.g., can calculate a channel's *capacity*
  => *fundamental limit on transmission rate.*

Computation
(a.k.a *transforming* information)

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- Multiplication: {x,y} ⇒ xy

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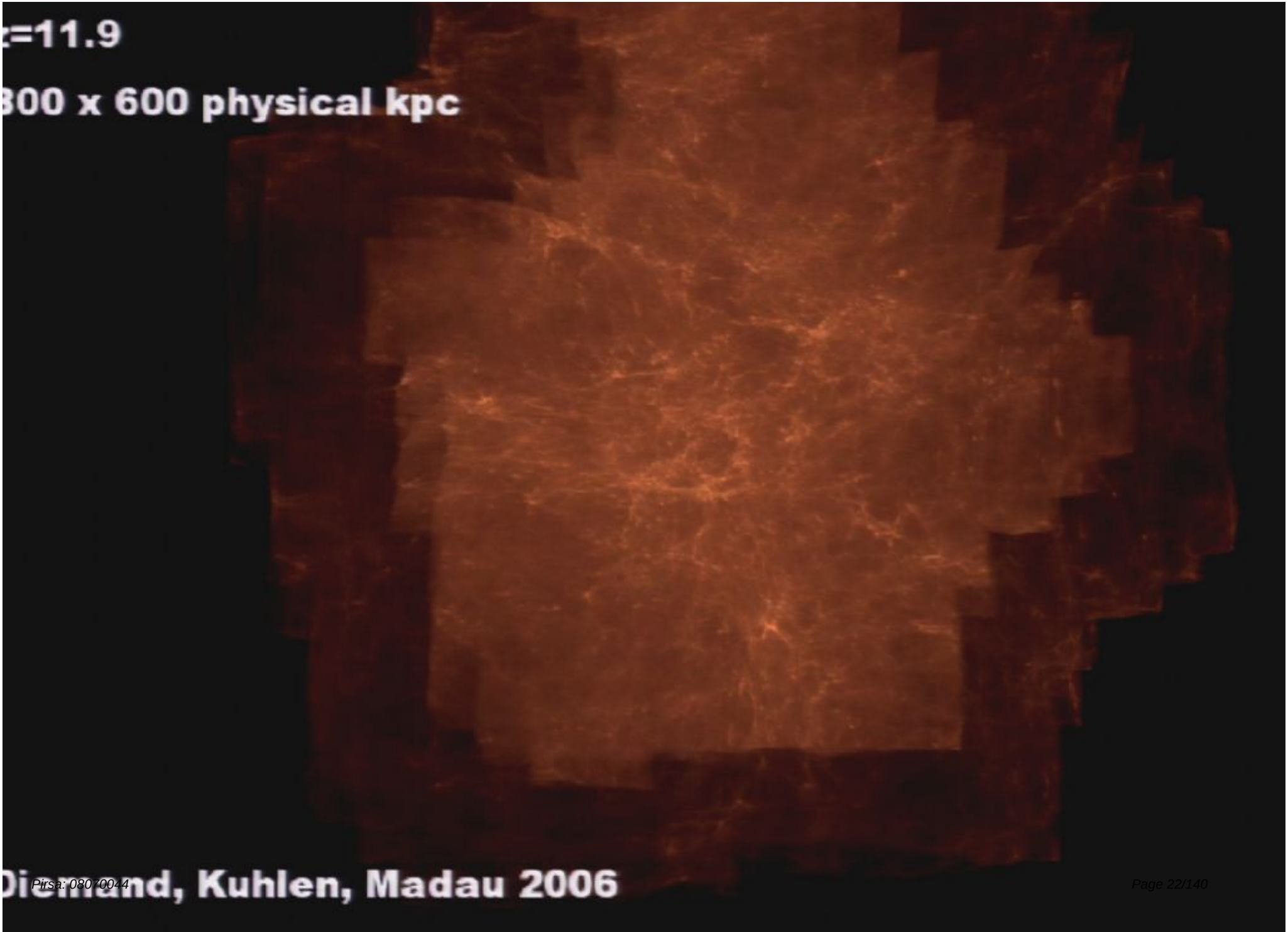
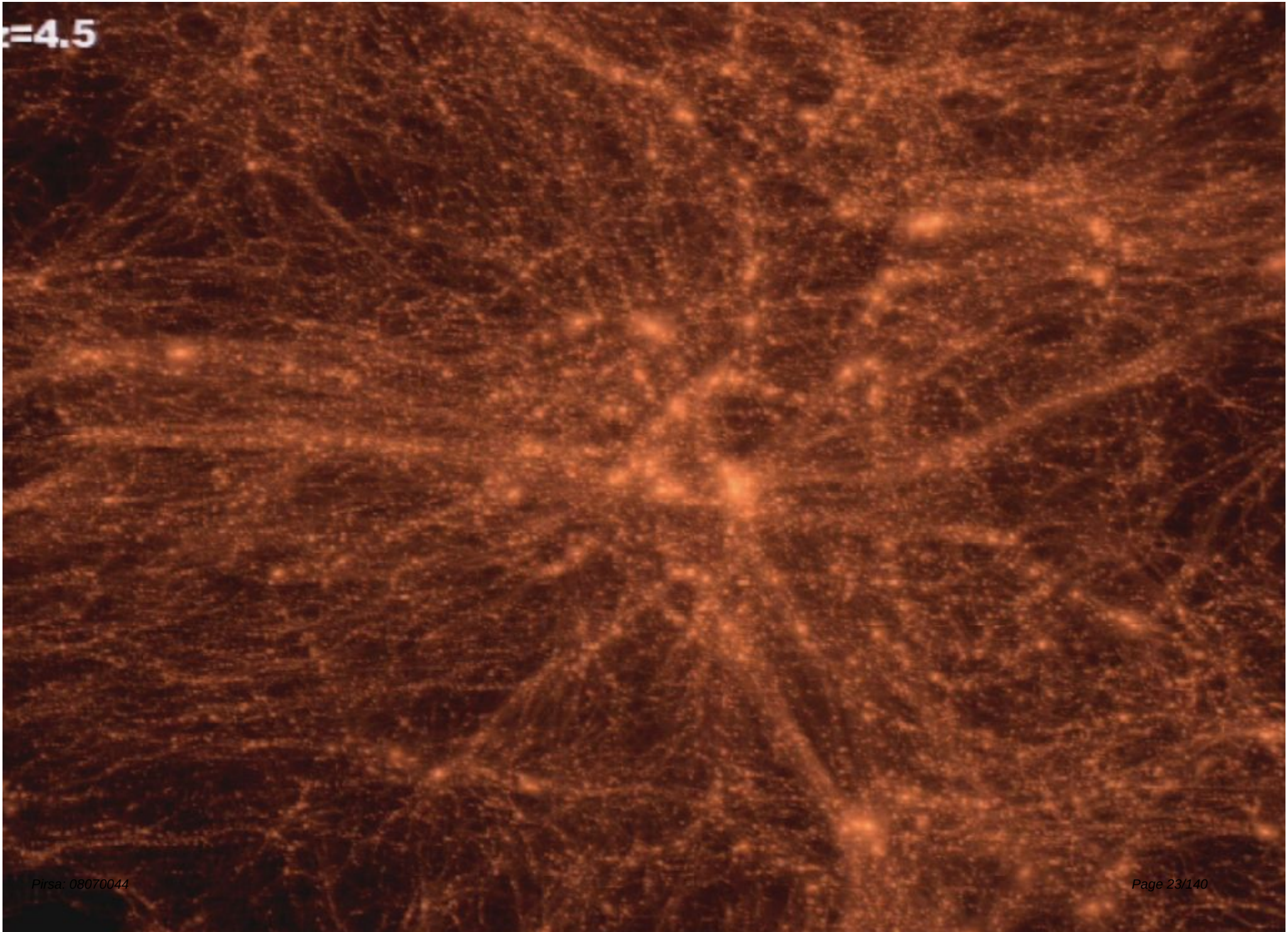
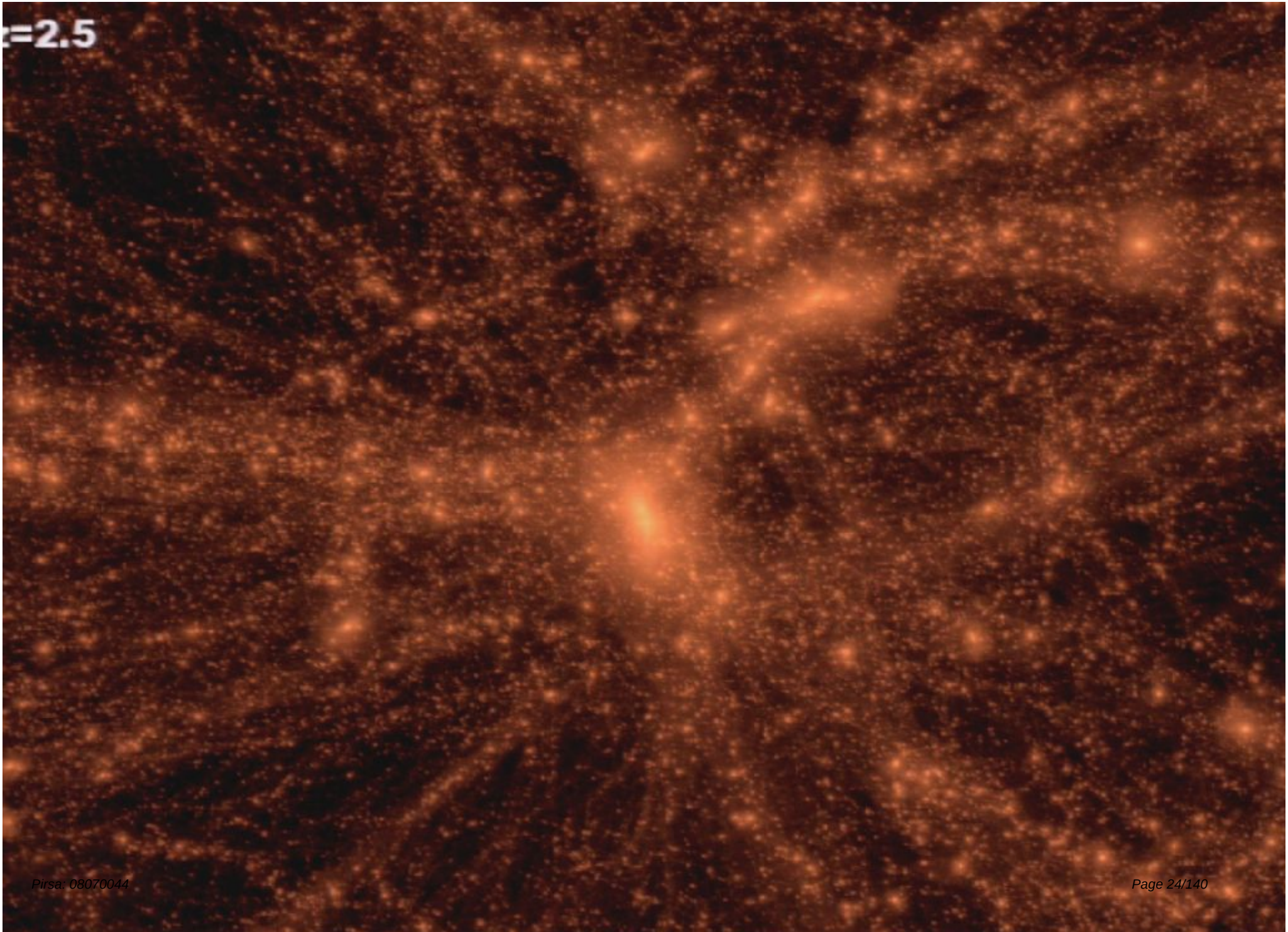
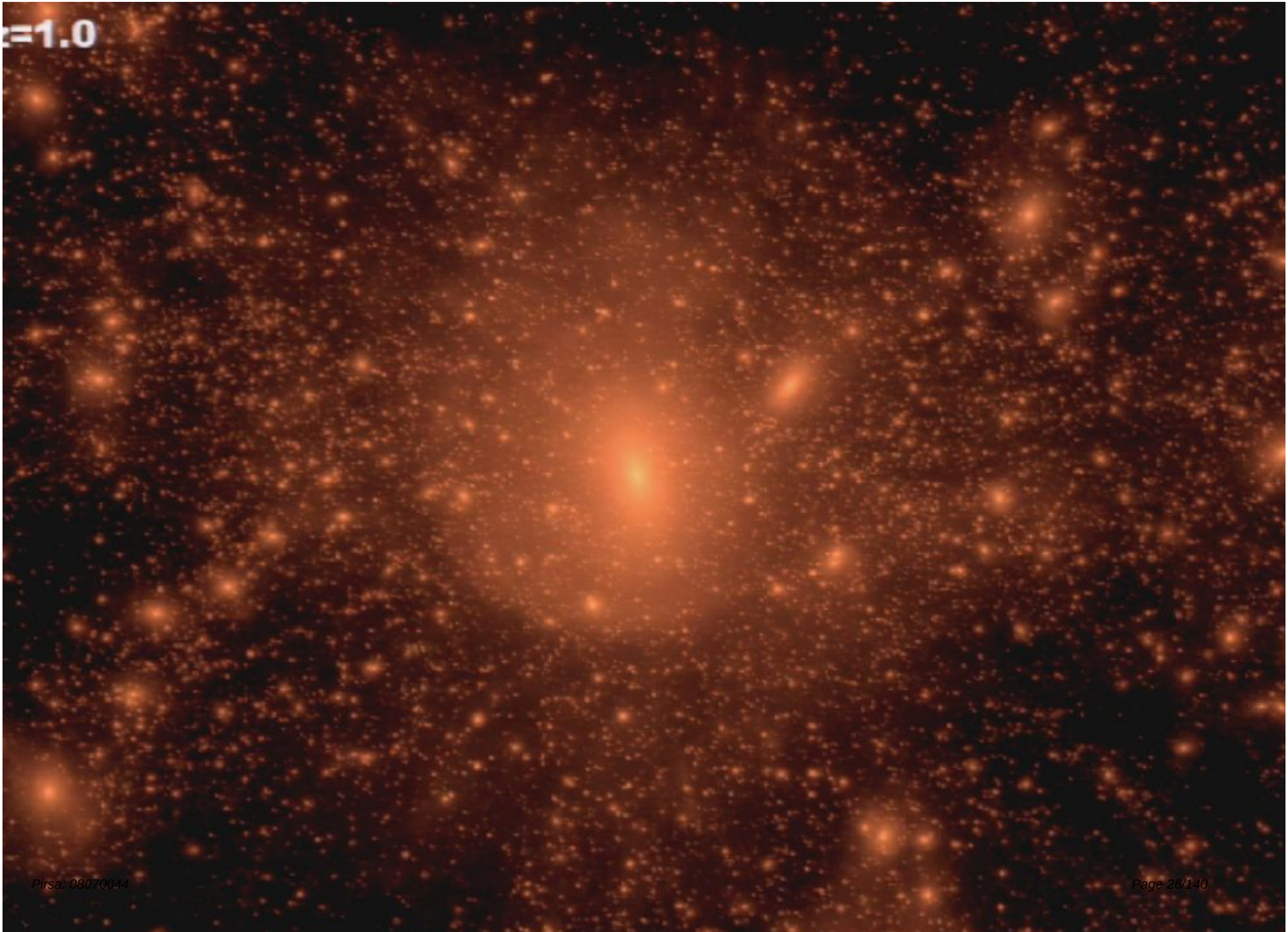

z=11.9
300 x 600 physical kpc
Diemand, Kuhlen, Madau 2006


z=4.5


z=2.5


z=1.7

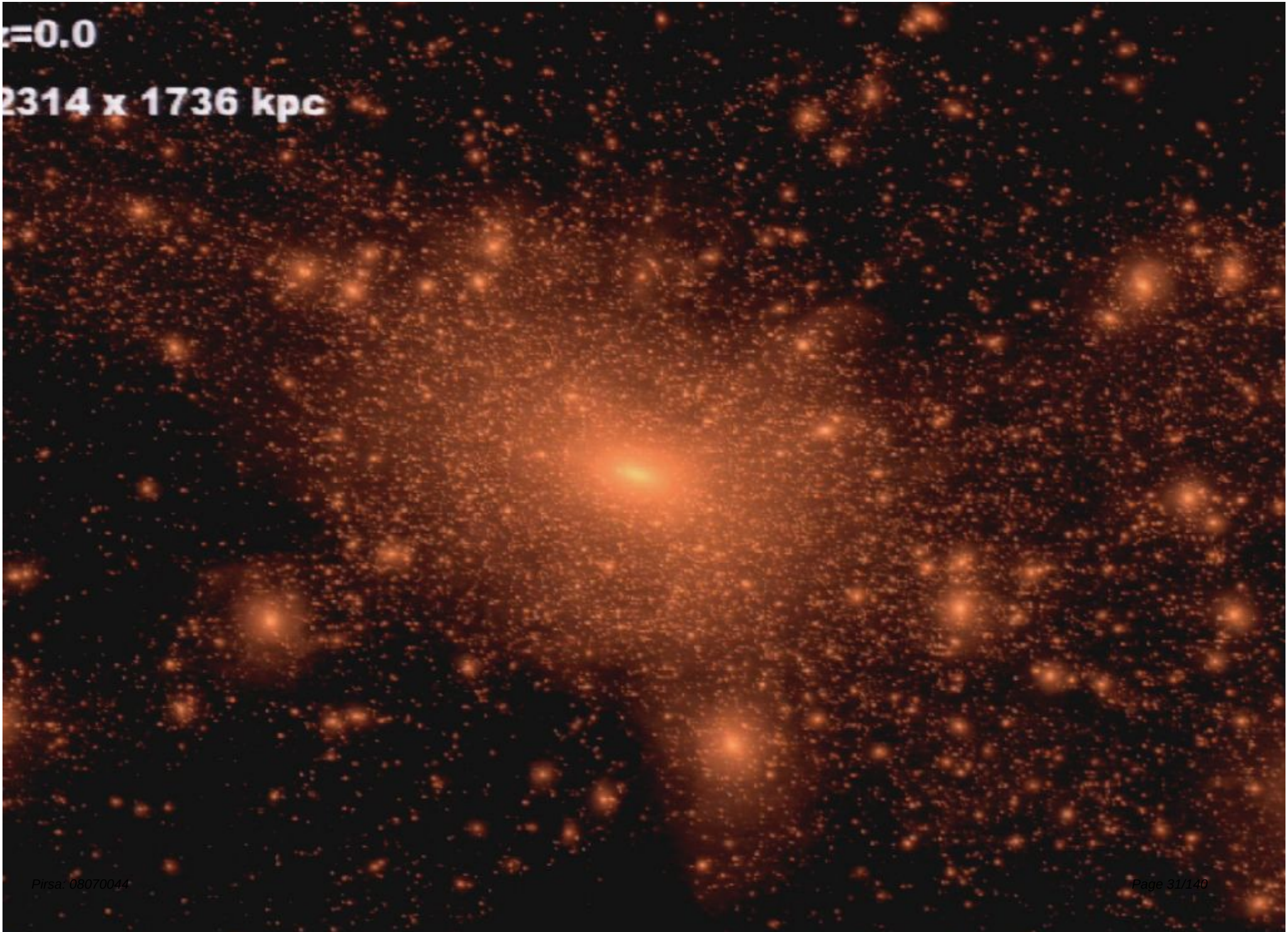

z=1.0


z=0.6


z=0.4


z=0.2

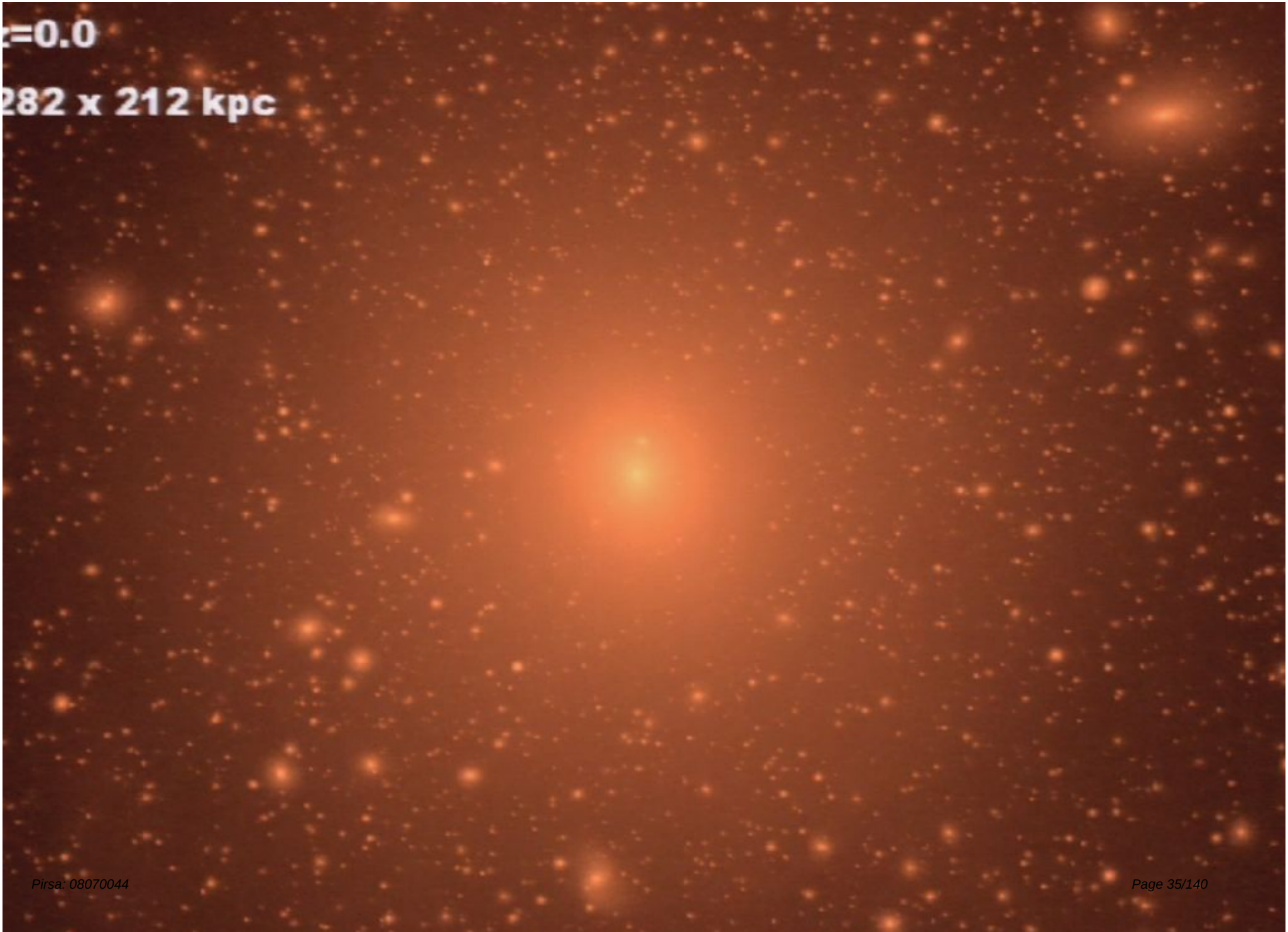

z=0.0


z=0.0
2314 x 1736 kpc


z=0.0
3659 x 2745 kpc


z=0.0
1770 x 1327 kpc


z=0.0
620 x 465 kpc


z=0.0
282 x 212 kpc


z=0.0
142 x 107 kpc
FNSNF
Fonds national suisse
Schweizerischer Nationalfonds
Fondo nazionale svizzero
Swiss National Science Foundation
NSF
UC SANTA CRUZ
NASA
Diemand, Kuhlen, Madau 2006

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- Rendering: {HTML} ⇒ {web page} $O(n)$
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- Factoring: xy ⇒ {x,y}
- Some problems are harder than others...

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(a.k.a. communicating *secretly*)

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- RSA *public-key* crypto: *Public* key (encryption) is x*y. *Private* key(decryption) is {x,y}

  Scorecard: complex, convenient, *computationally* secure

How Quantum is Different

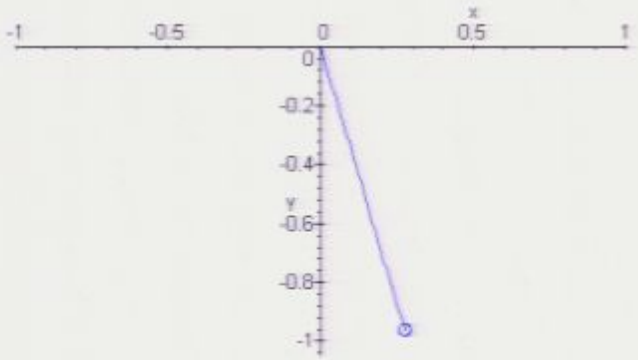
Nature is weirder than we thought (c. 1900)

- Experimental symptoms:
  * atoms don't collapse
  * light comes in chunks *and* it diffracts
  * glowing charcoal radiates *finite* energy
- Physical systems follow unexpected rules!
  * "*The particle has well-defined position and momentum*" is **not** true.
  * "*The photon's energy is an integer multiple of its frequency*" ***is*** *true.*
- Conclusion: We needed a new set of states to describe physical systems in our quantum world.

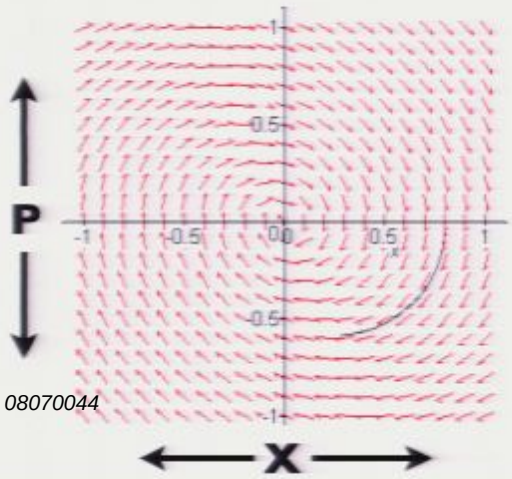
States of Classical Systems

Example I: Pendulum

Simple Pendulum in Real Space : Damped with Coeff = 0.4



Simple Pendulum in Phase Space : Damped with Coef f= 0.4



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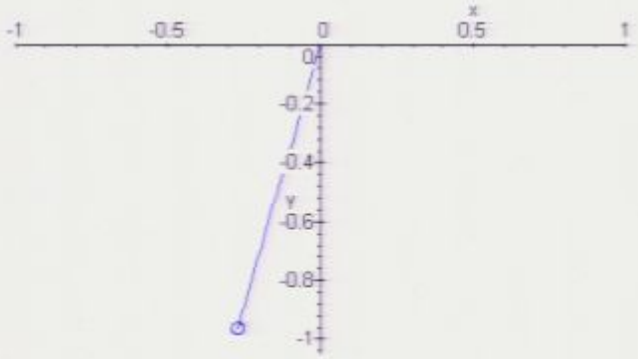

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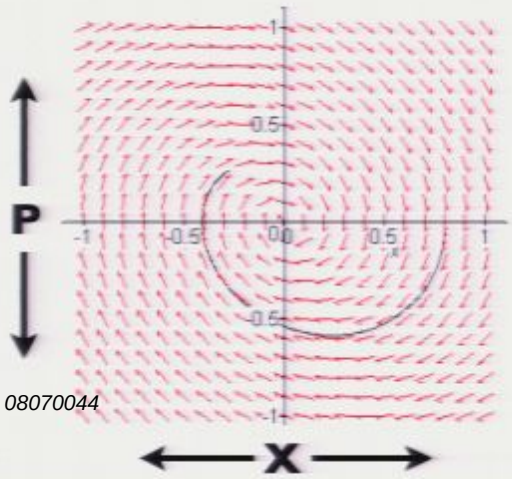

Example 2: A Switch

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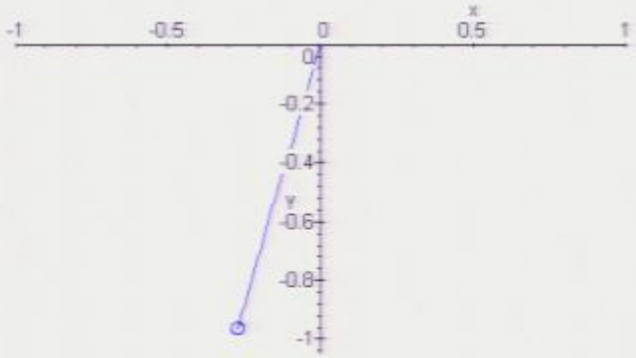

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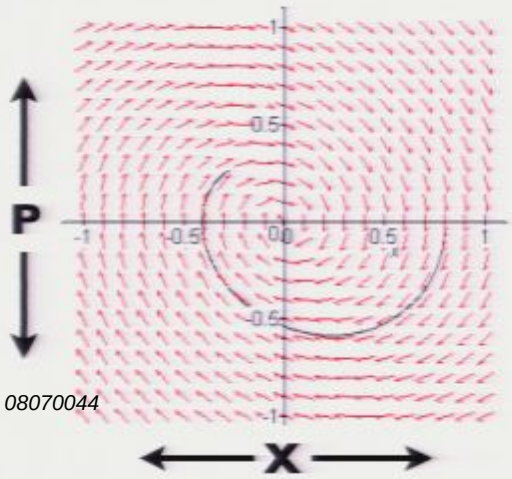

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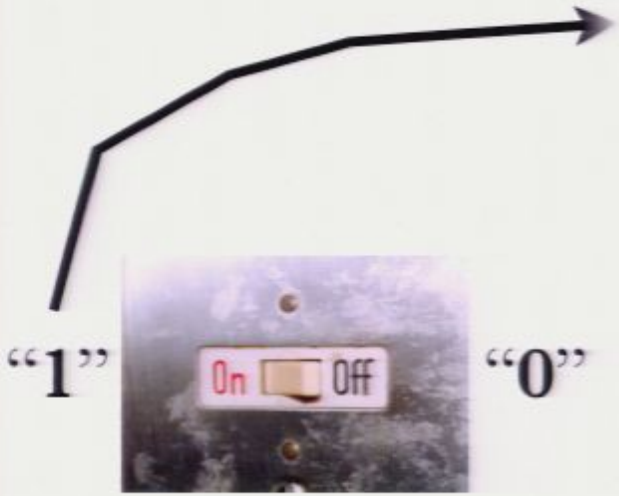

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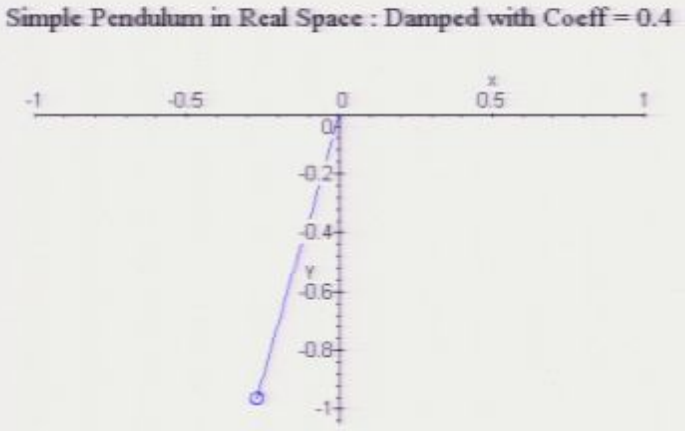

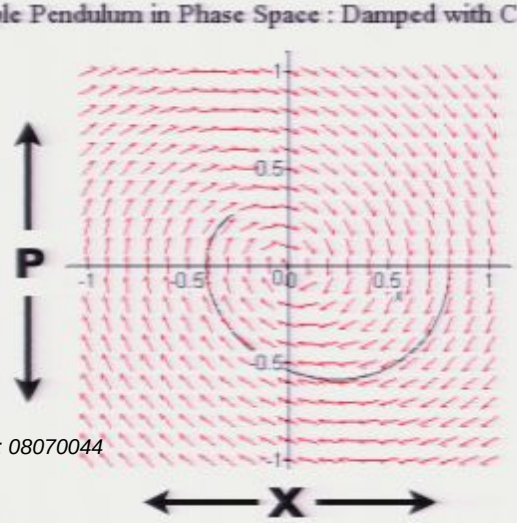

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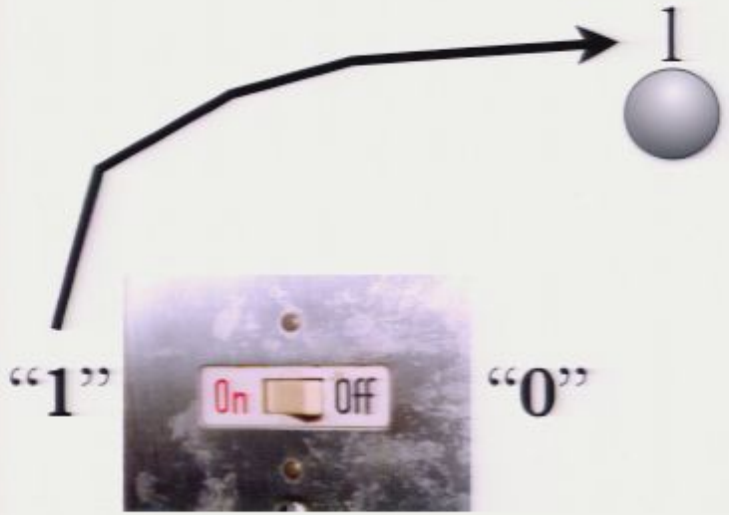

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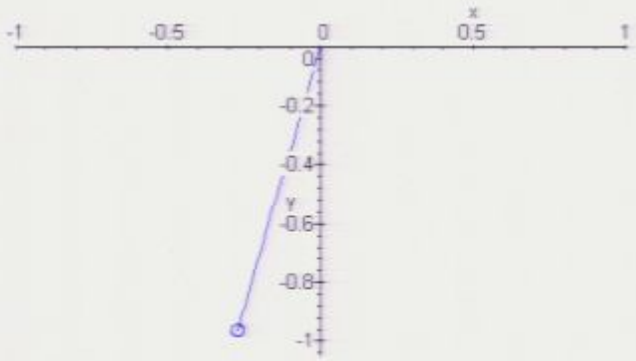

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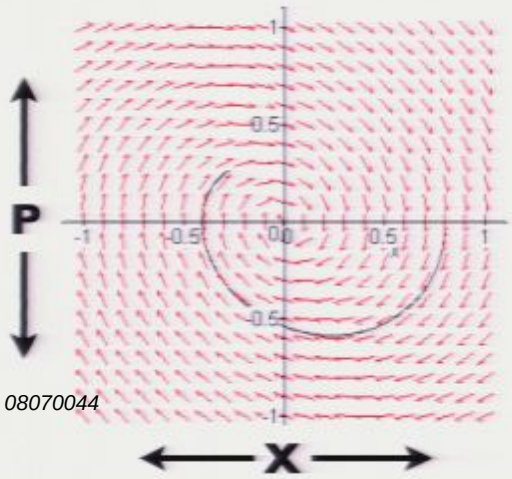

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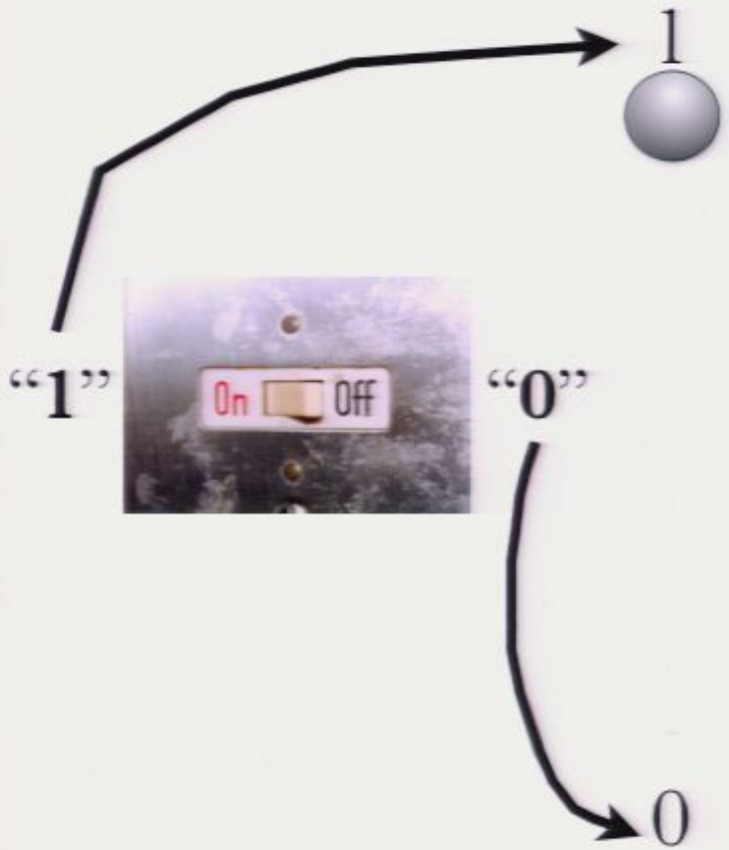

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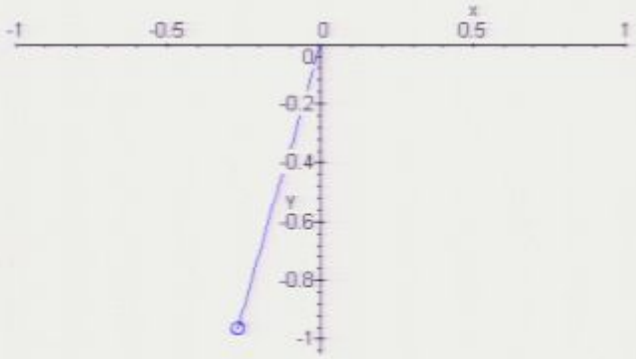

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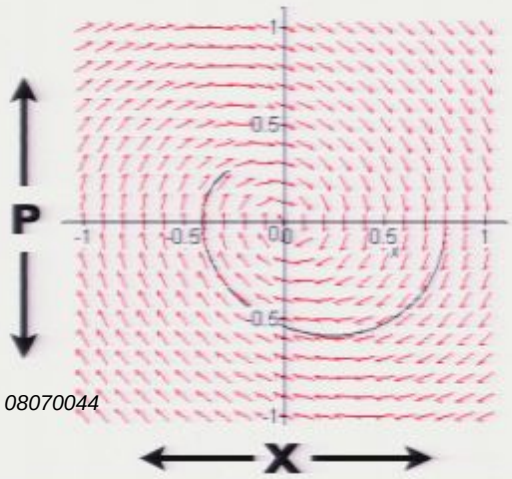

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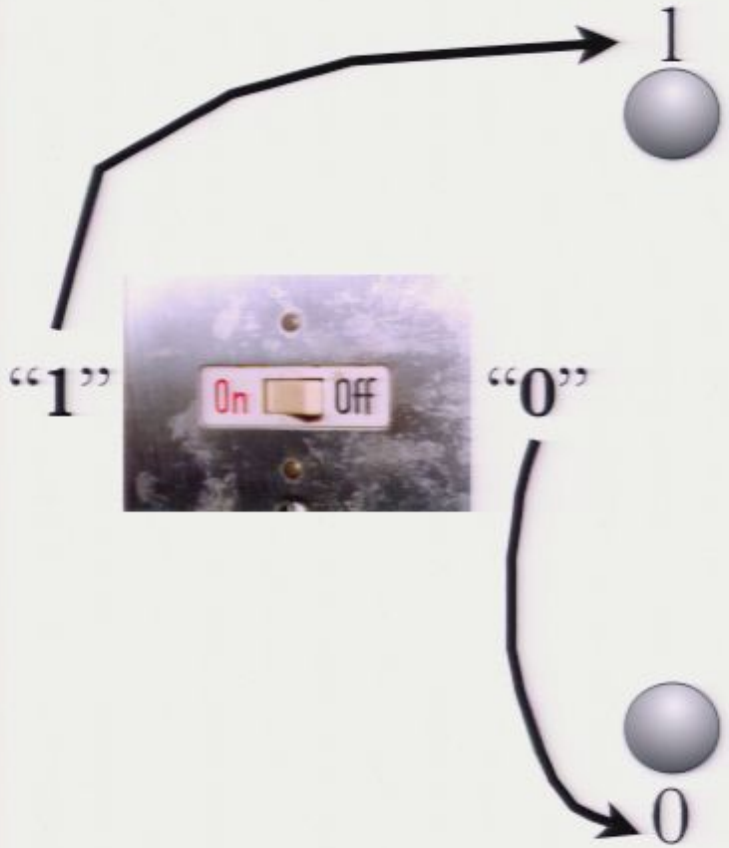

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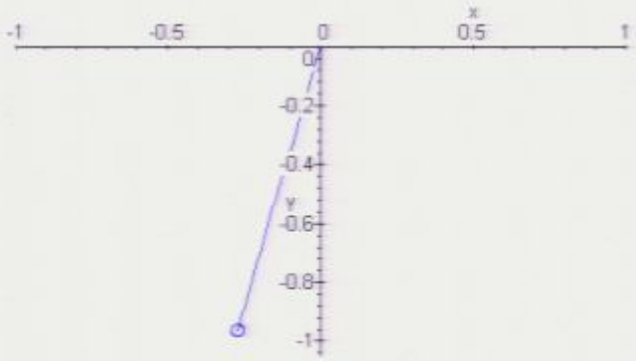

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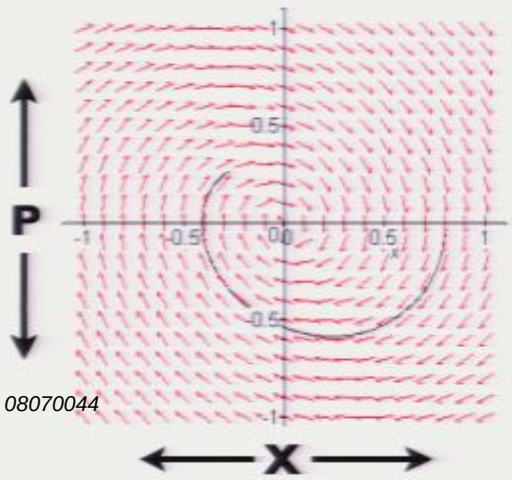

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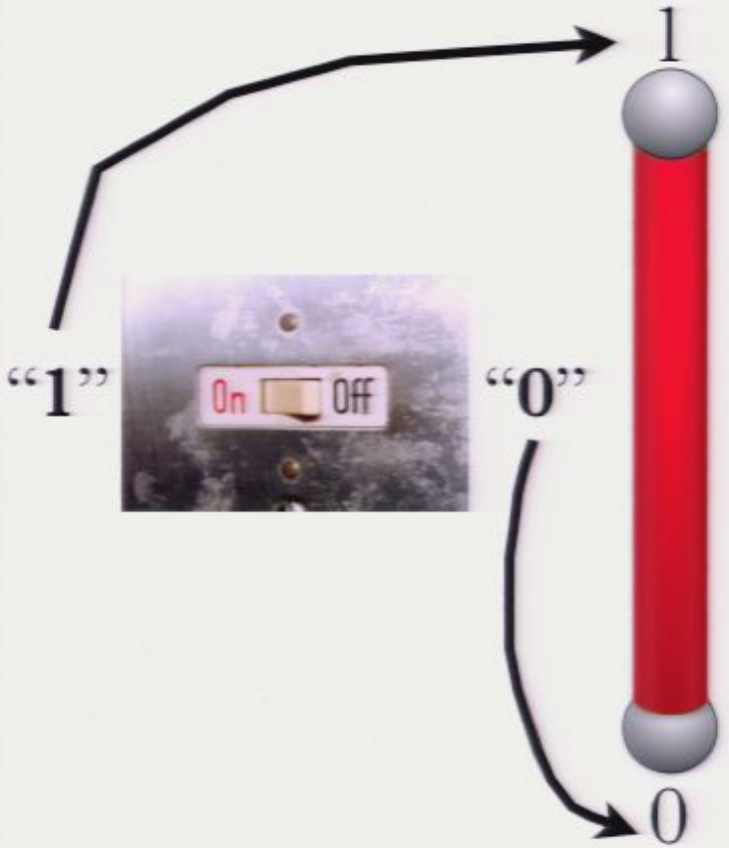
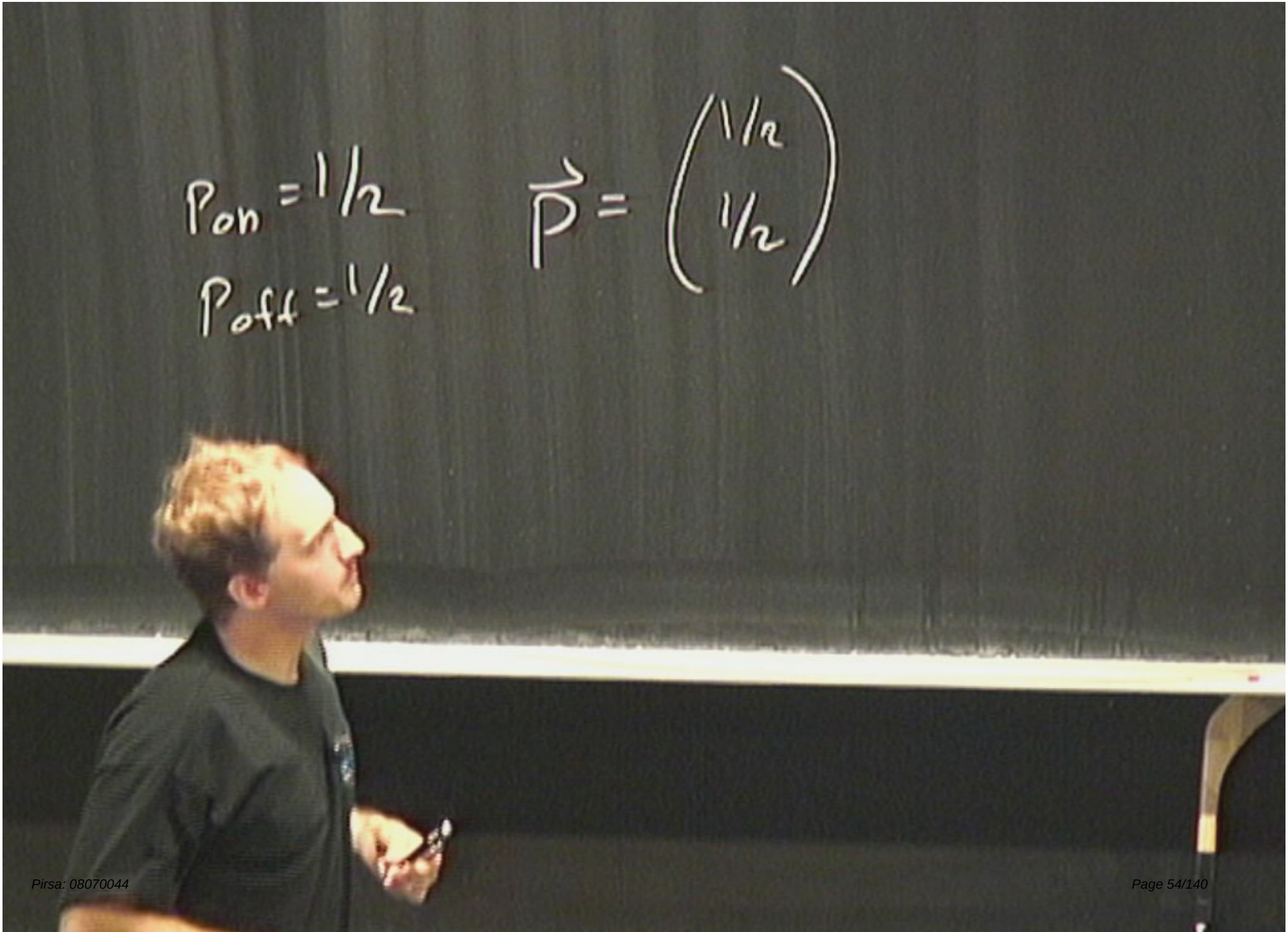
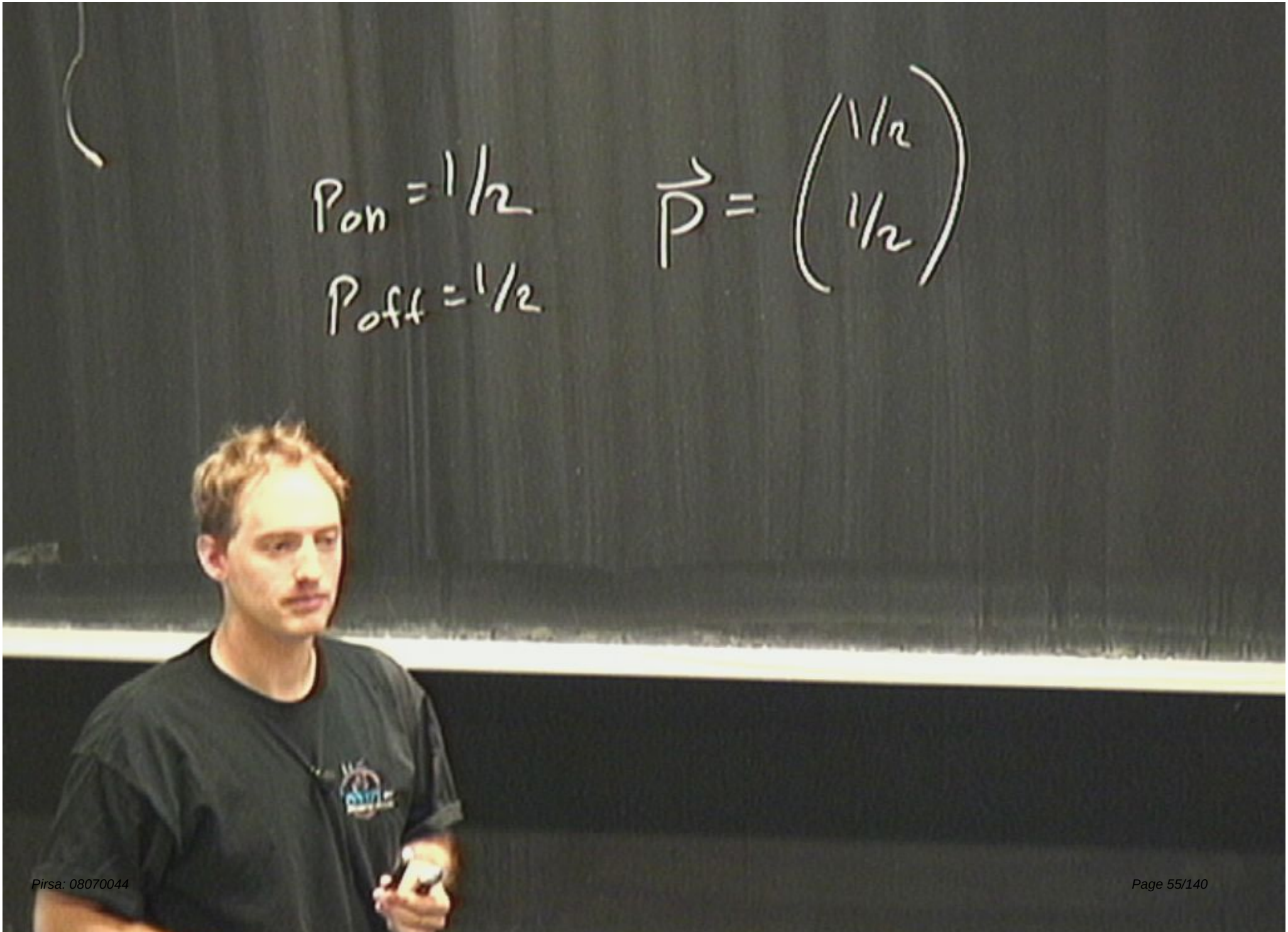



$P_{on} = 1/2$
$P_{off} = 1/2$
$\vec{p} = \begin{pmatrix} 1/2 \\ 1/2 \end{pmatrix}$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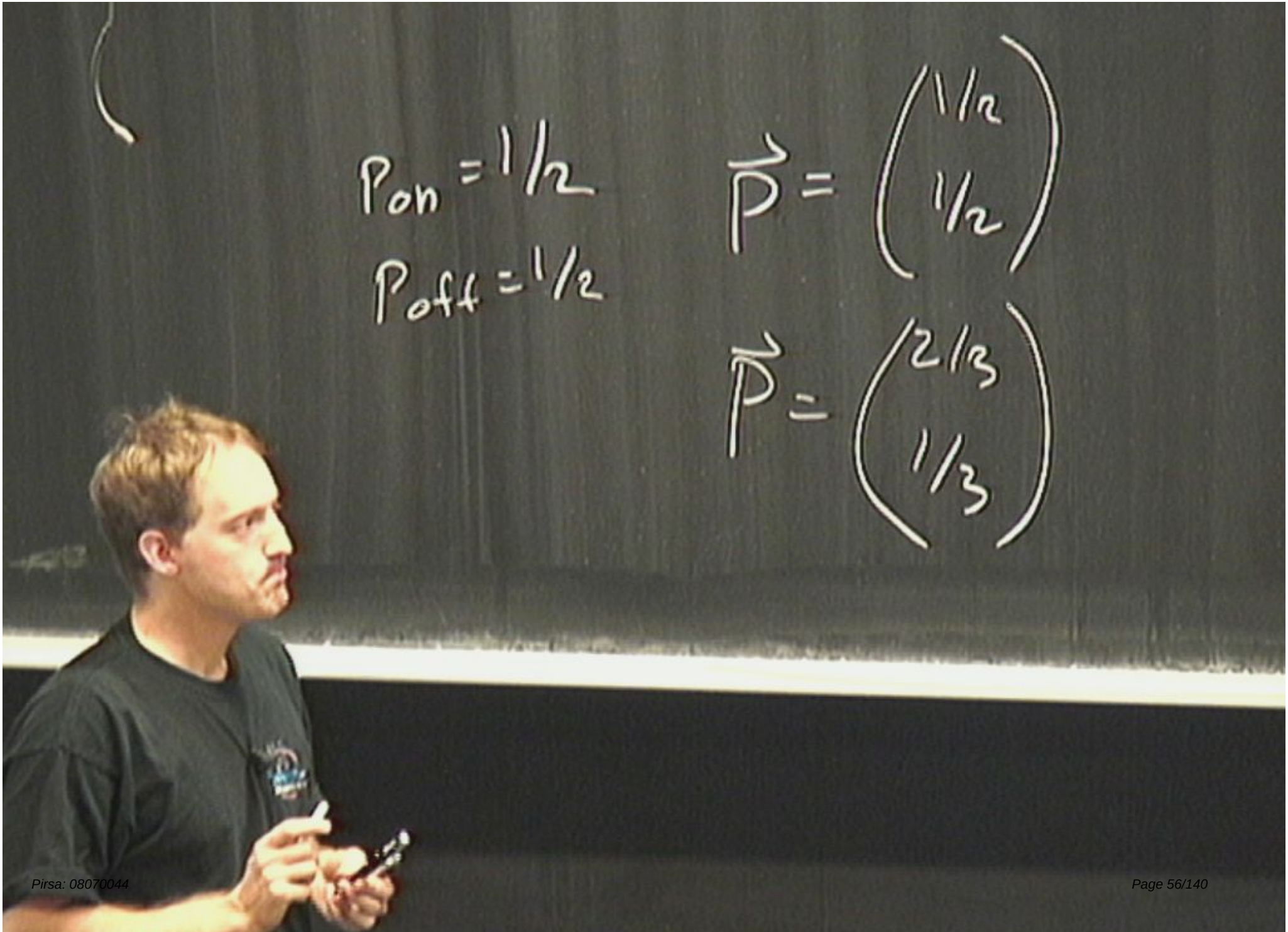
$P_{on} = 1/2$
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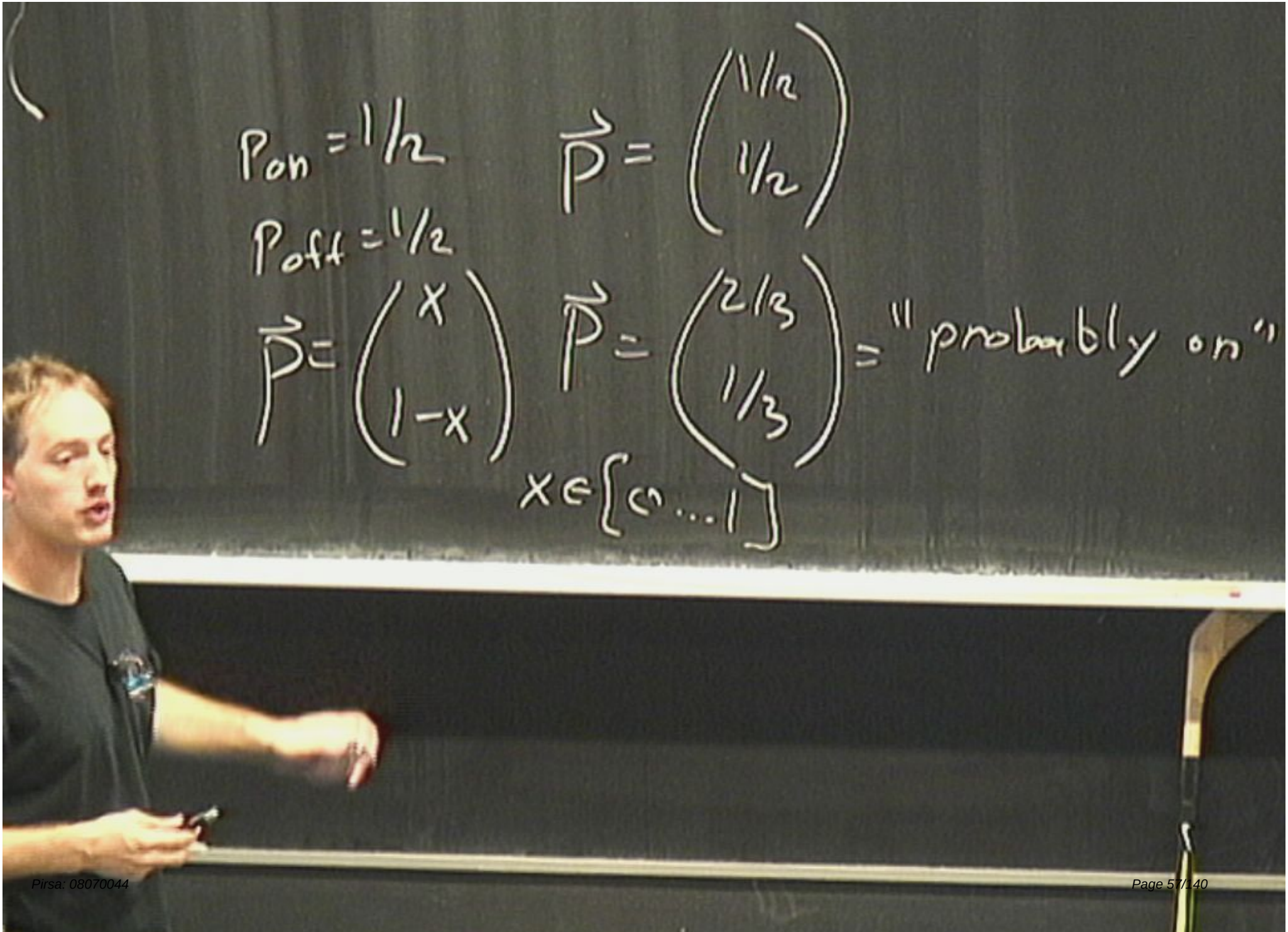
$\vec{P} = \begin{pmatrix} 1/2 \\ 1/2 \end{pmatrix}$
$\vec{P} = \begin{pmatrix} 2/3 \\ 1/3 \end{pmatrix}$


$P_{on} = 1/2$
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$\vec{p} = \begin{pmatrix} 1/2 \\ 1/2 \end{pmatrix}$
$\vec{p} = \begin{pmatrix} x \\ 1-x \end{pmatrix}$
$\vec{p} = \begin{pmatrix} 2/3 \\ 1/3 \end{pmatrix}$ = "probably on"
$x \in [0 \ldots 1]$

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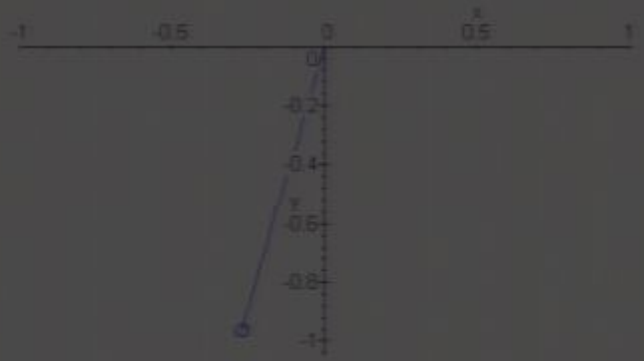

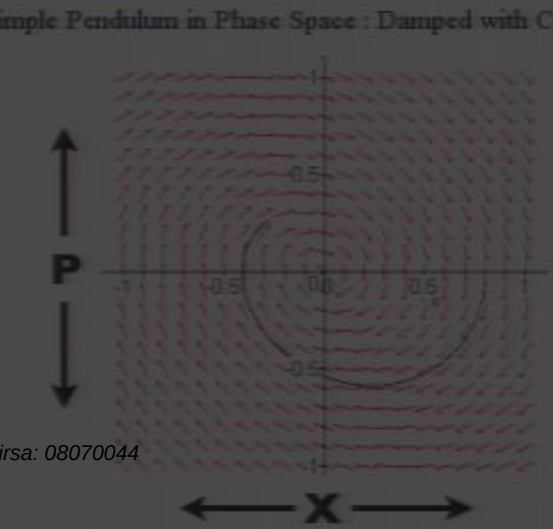

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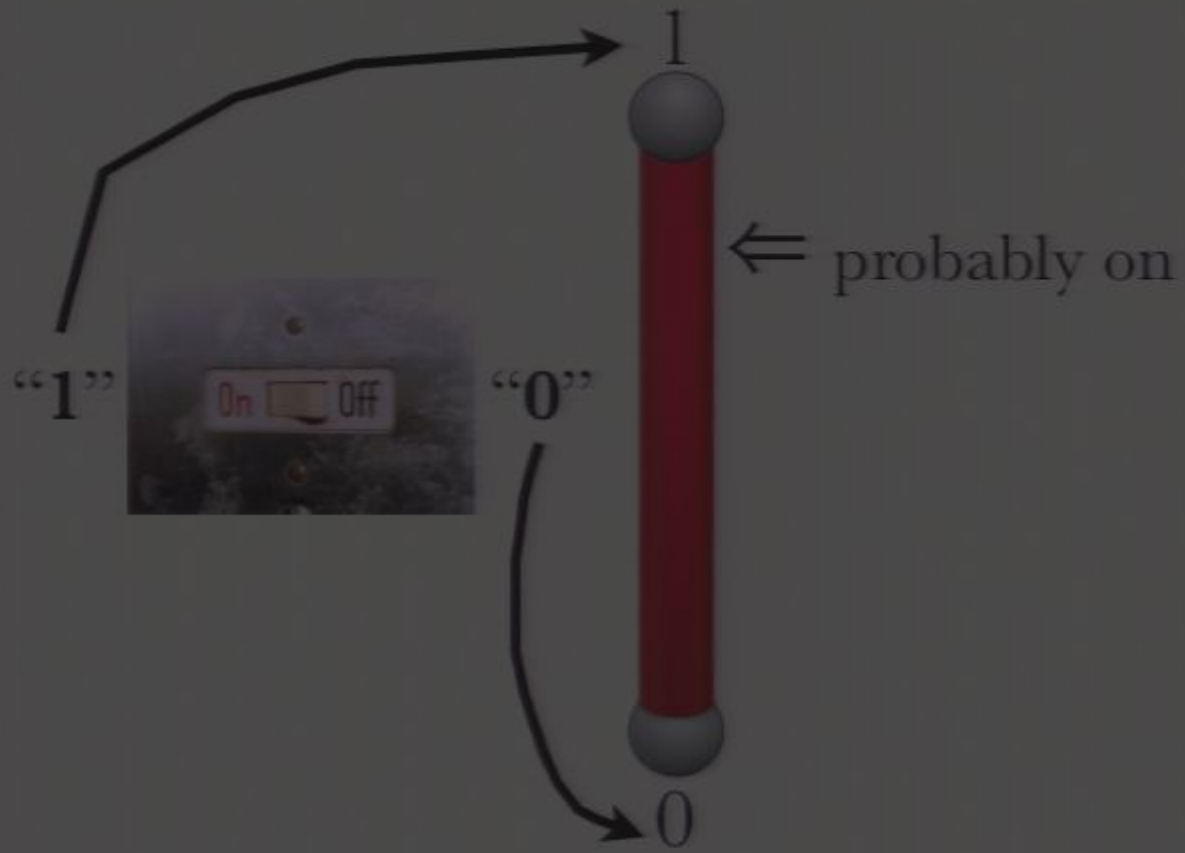

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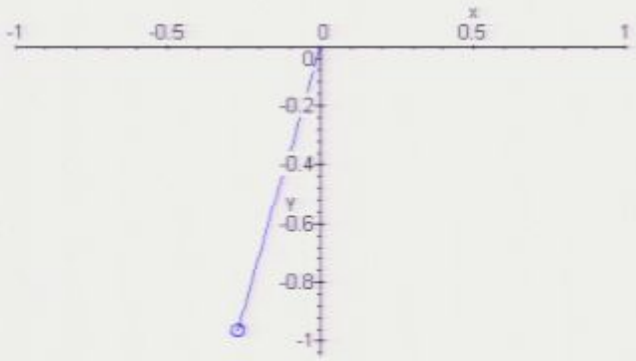
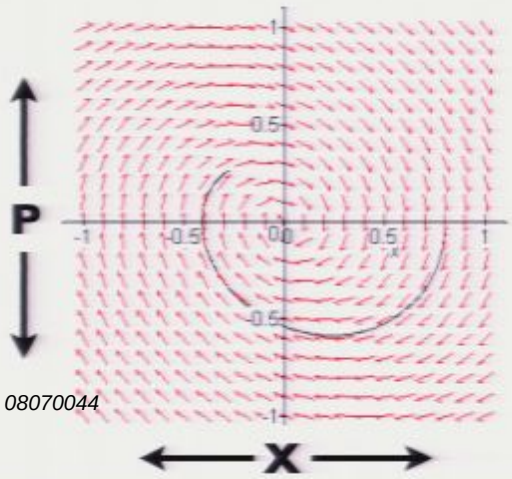
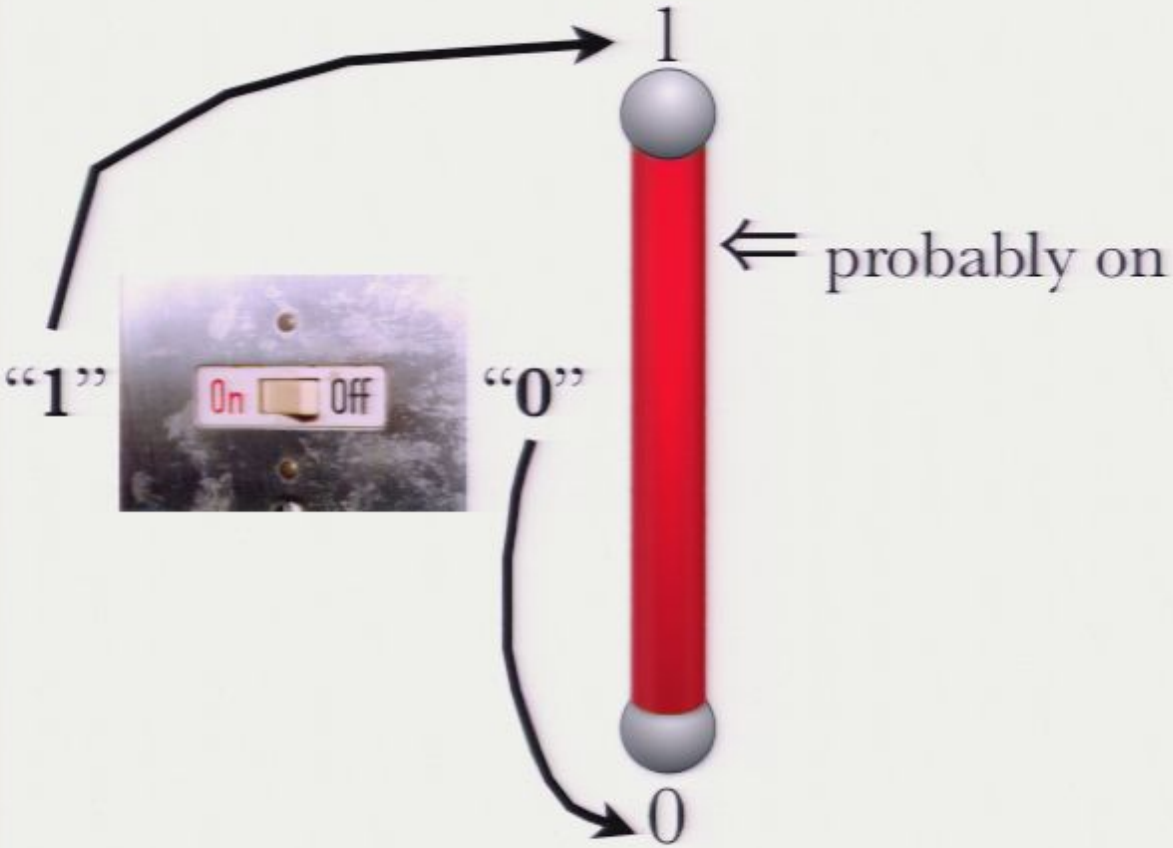


Simple Pendulum in Phase Space : Damped with Coef f= 0.4



Example 2: A Switch



States of Classical Systems

Example 1: Pendulum

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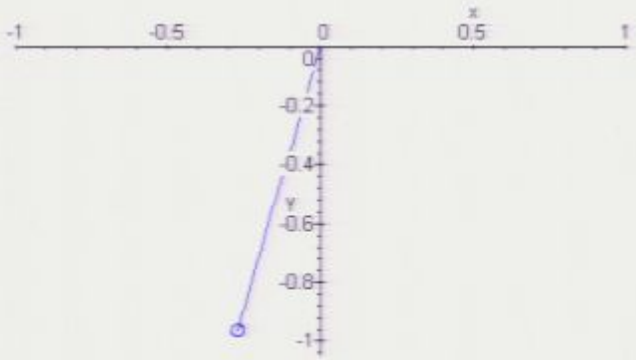

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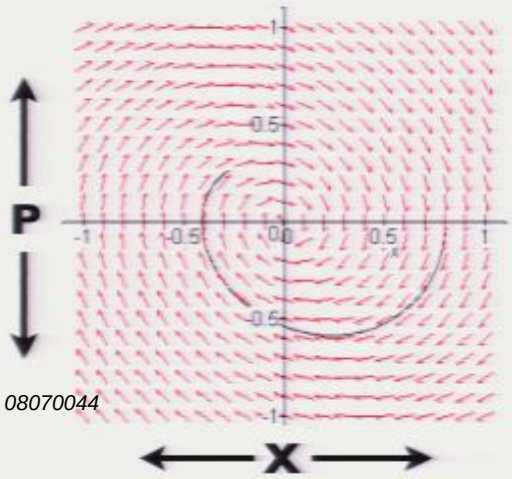

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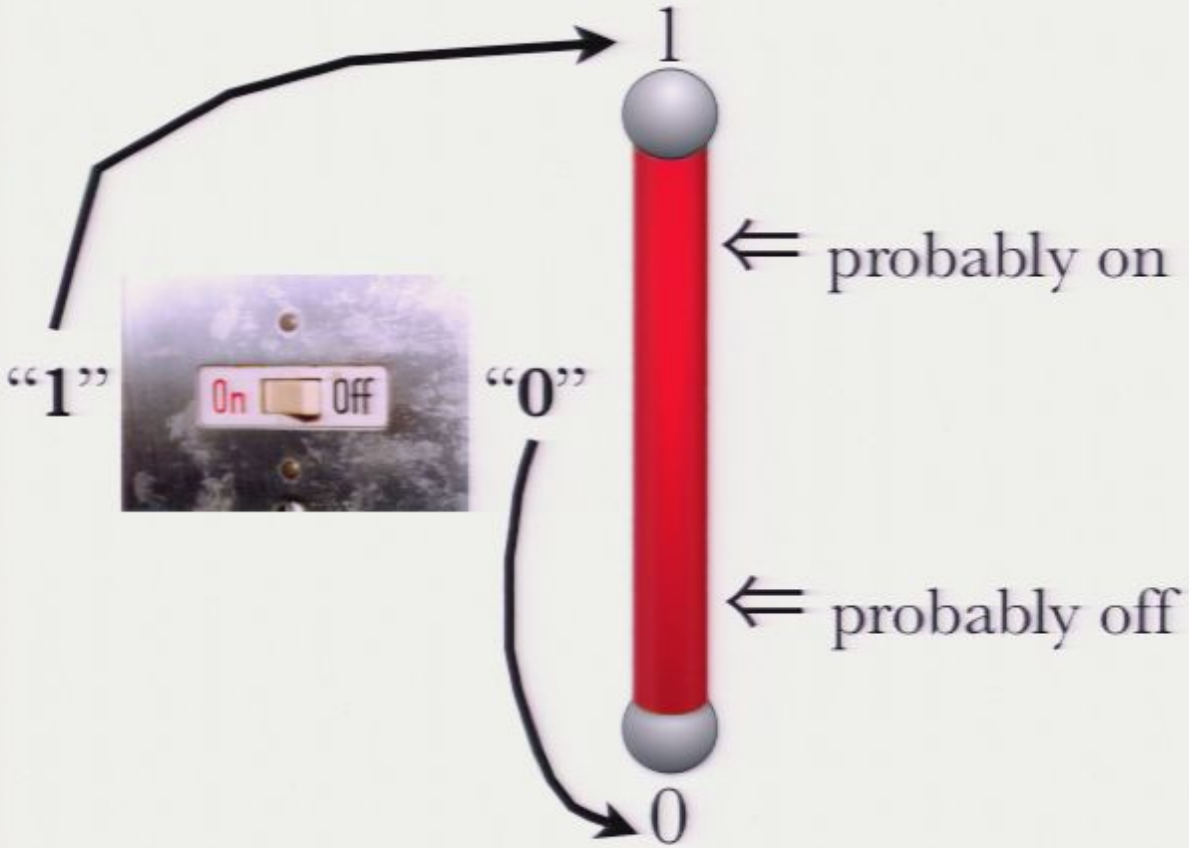

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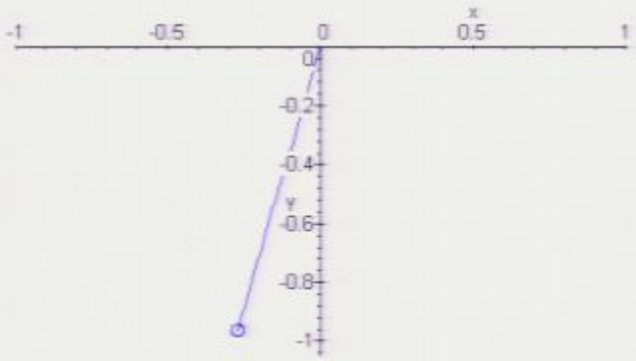

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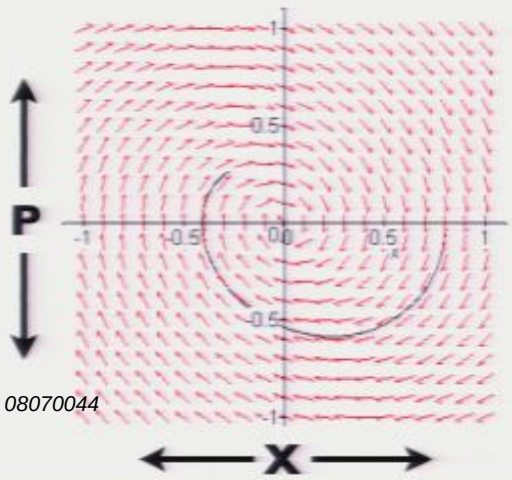

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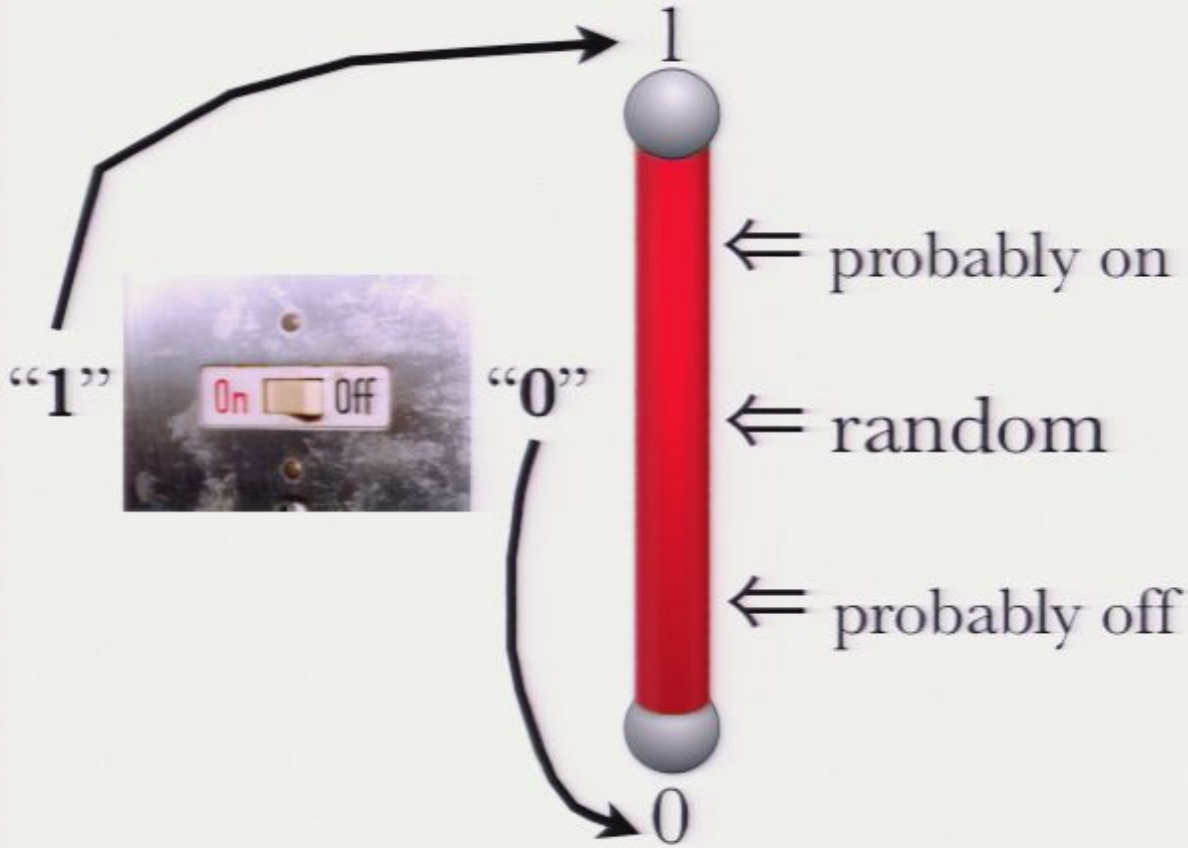

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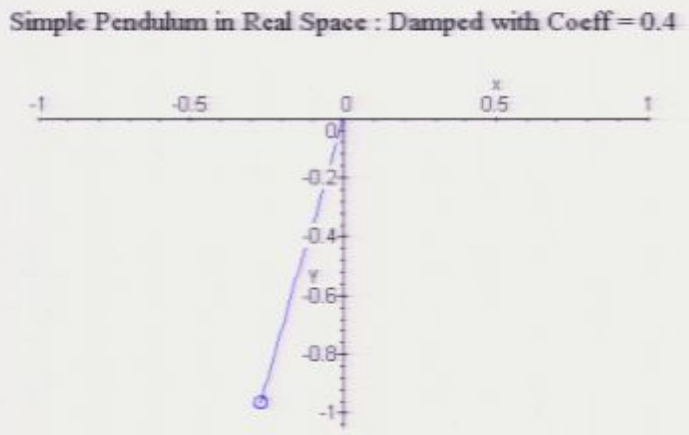

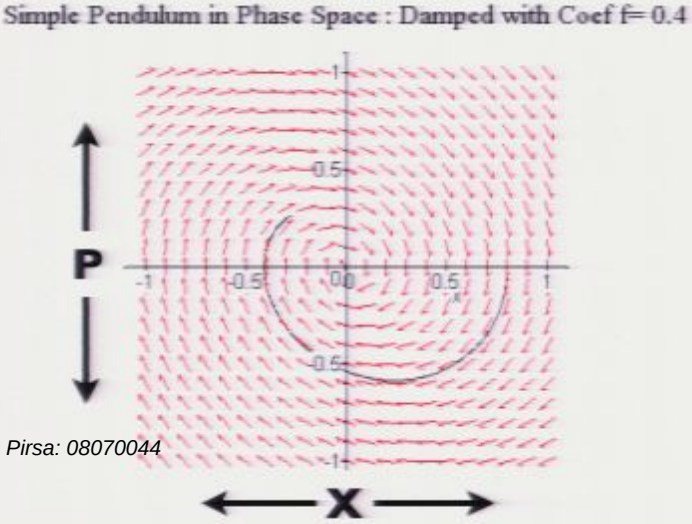

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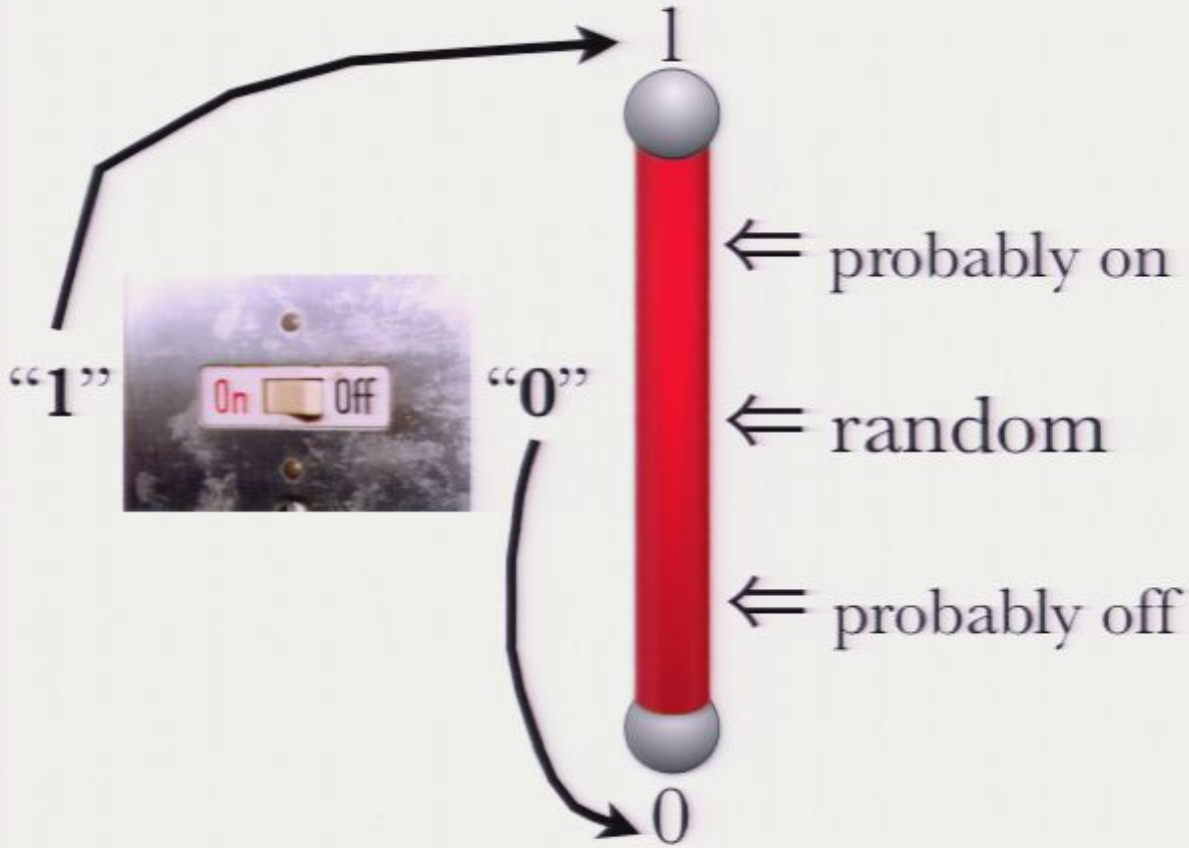

***Reversible* dynamics = permutations of {0,1}.**

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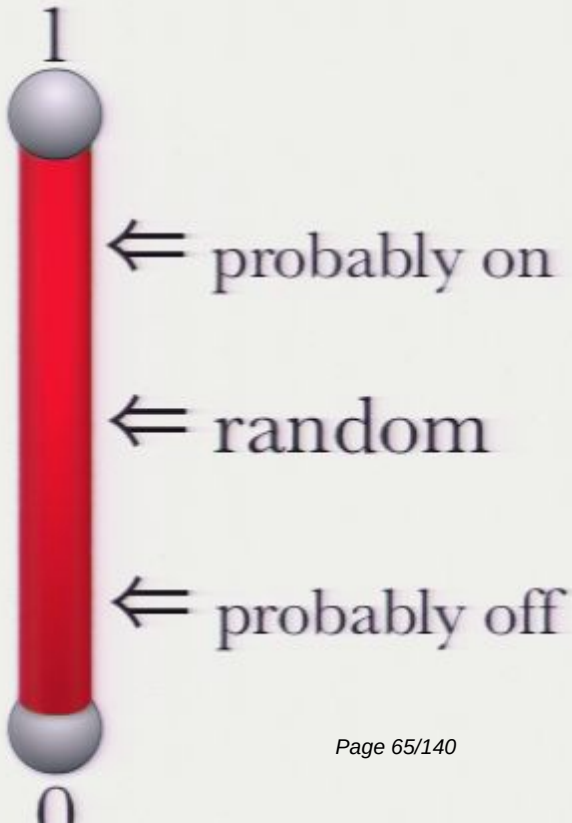

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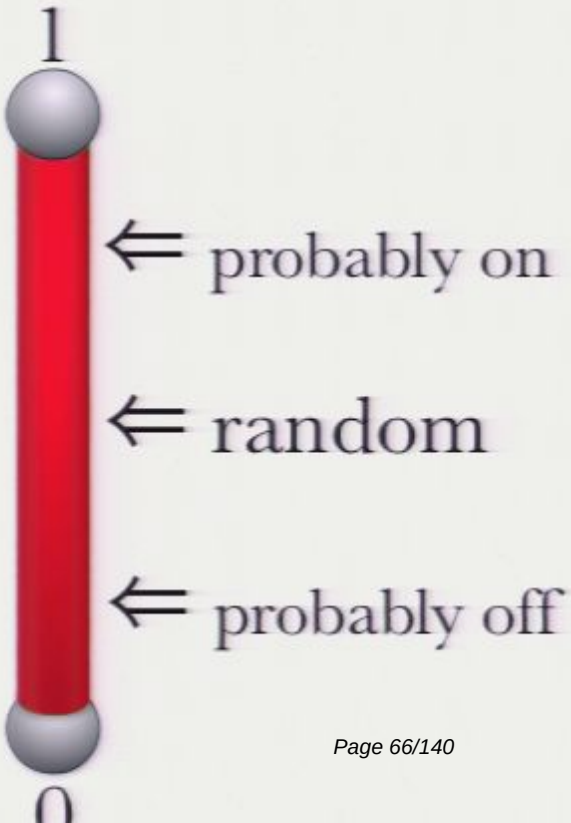

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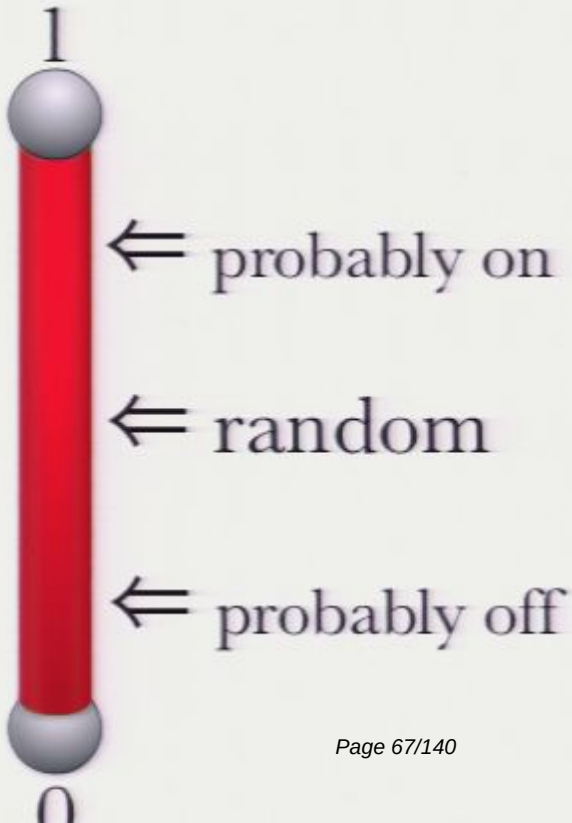

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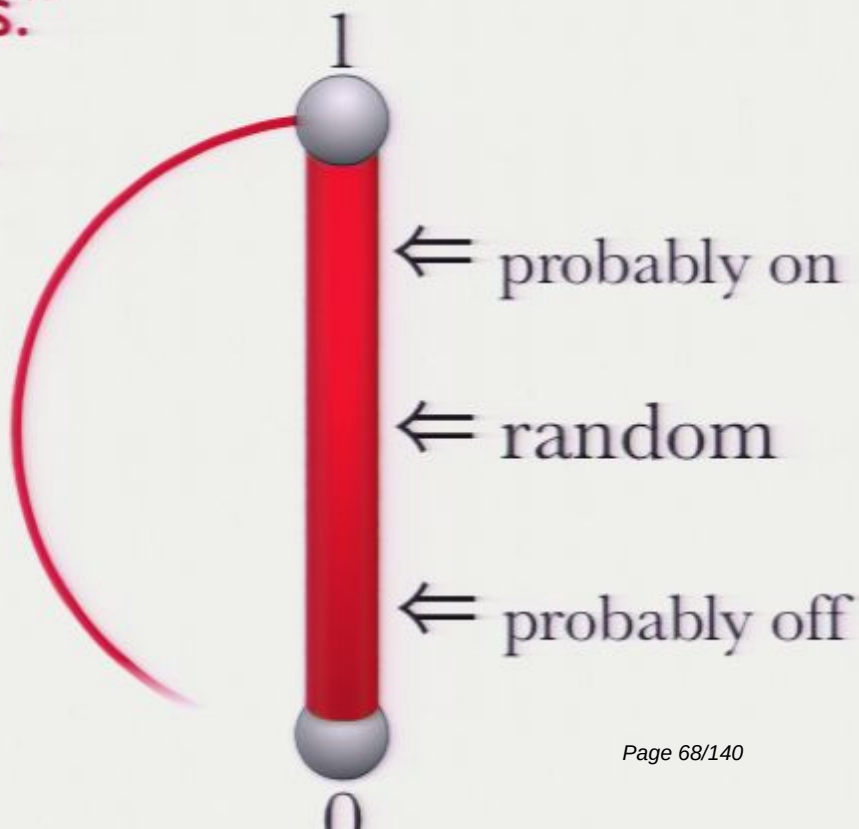

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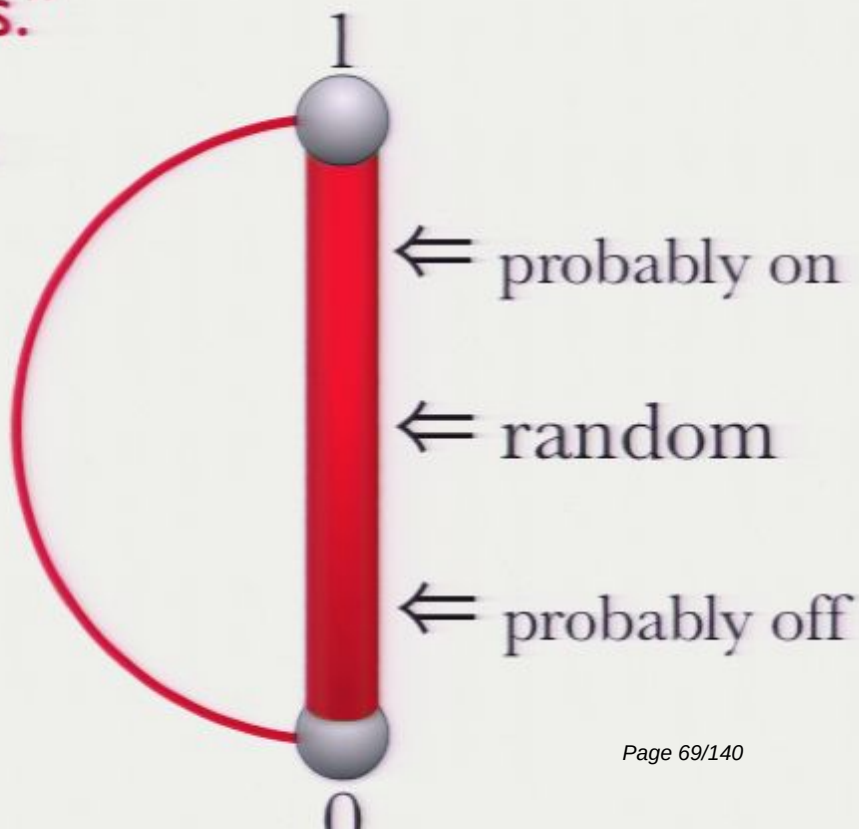

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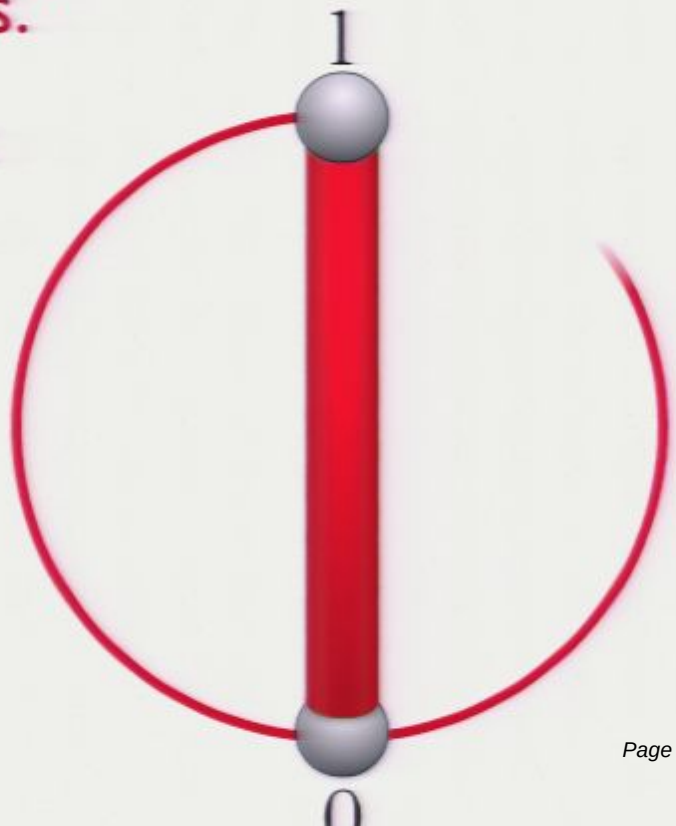

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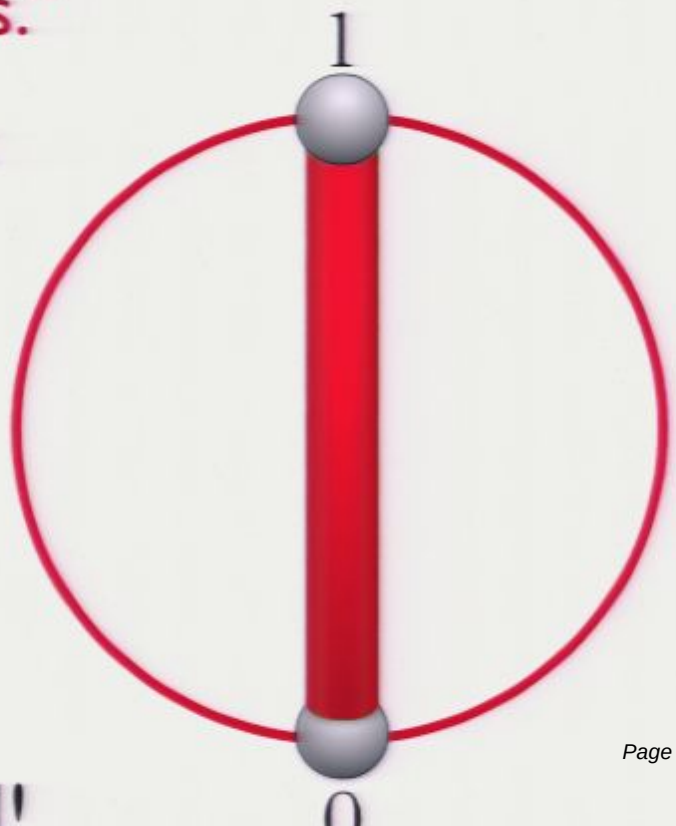

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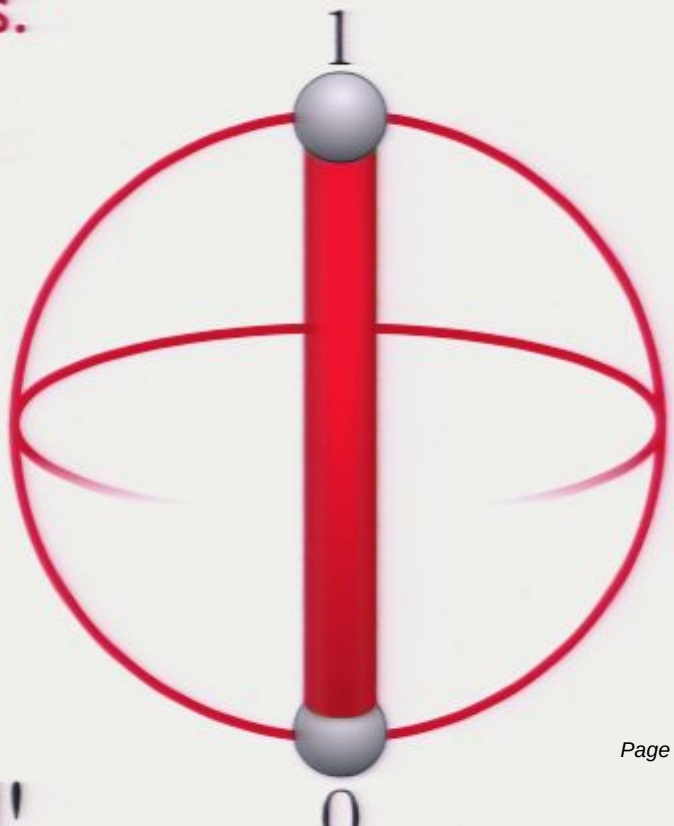

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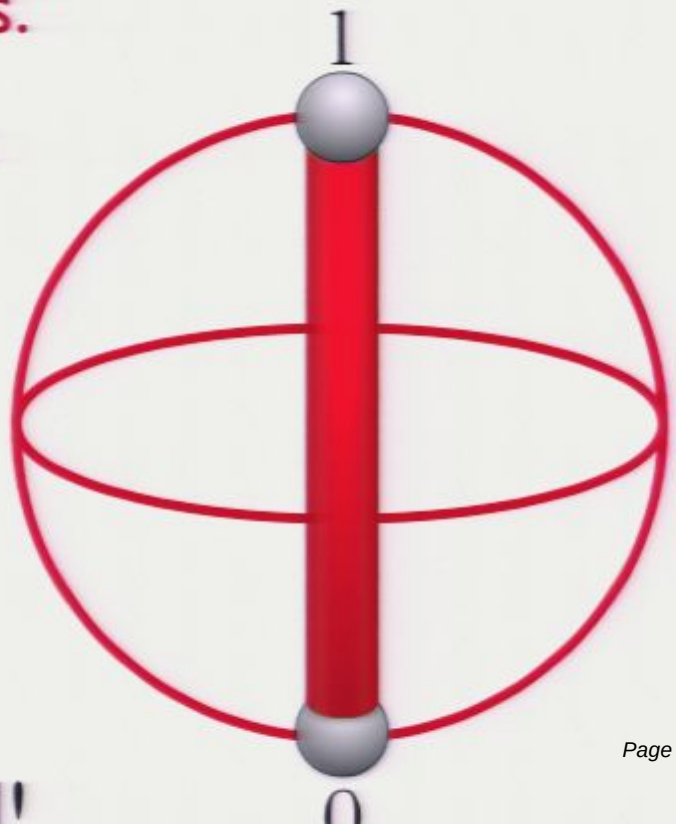
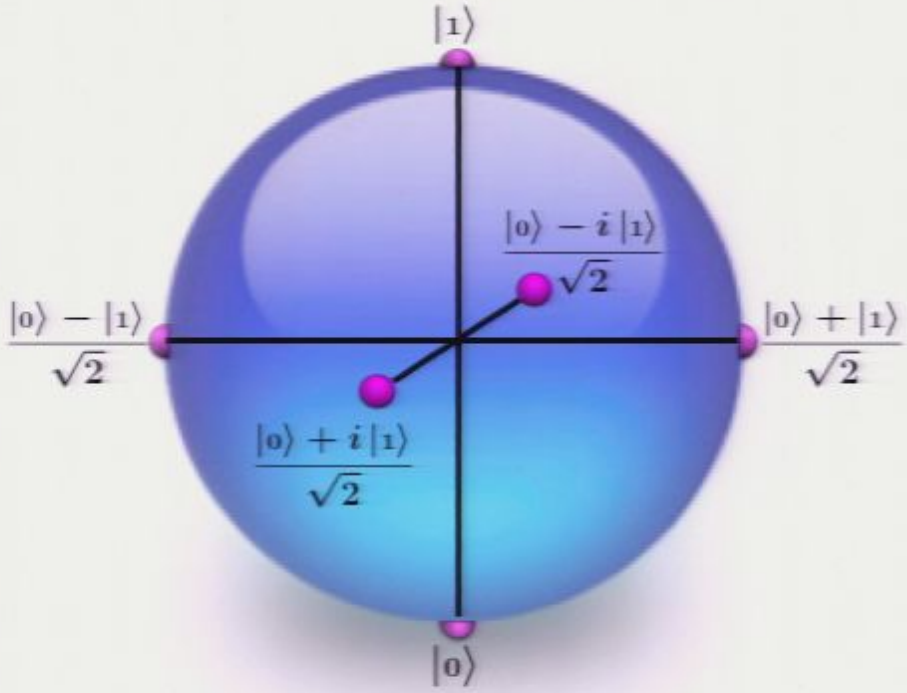


Quantum States

Classical Bit (Probabilistic)

Quantum Bit & the Bloch Sphere



State predicts outcome of measurements.

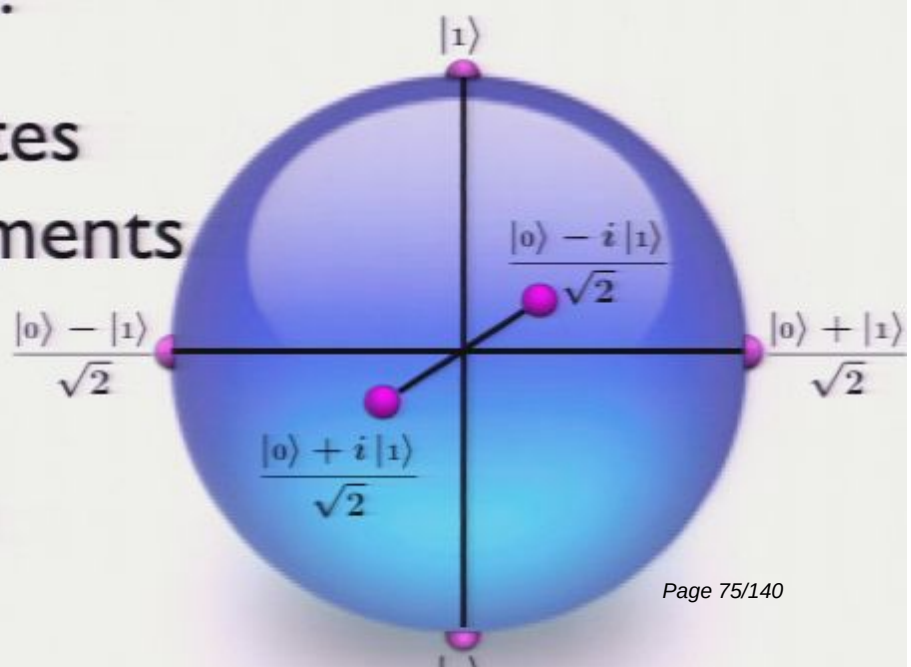
Vector space: $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle \Longrightarrow |\psi\rangle = \begin{pmatrix} \alpha \\ \beta \end{pmatrix}$

Quantum Measurements

- Sole purpose of a state is *to predict the outcome of measurements*.
- Classical bit ⇒ one measurement:

  "Is the switch **on**, or **off**?"

- Quantum bit has more states
  ⇒ must be more measurements
- Symmetry implies
  each axis ⇔ measurement



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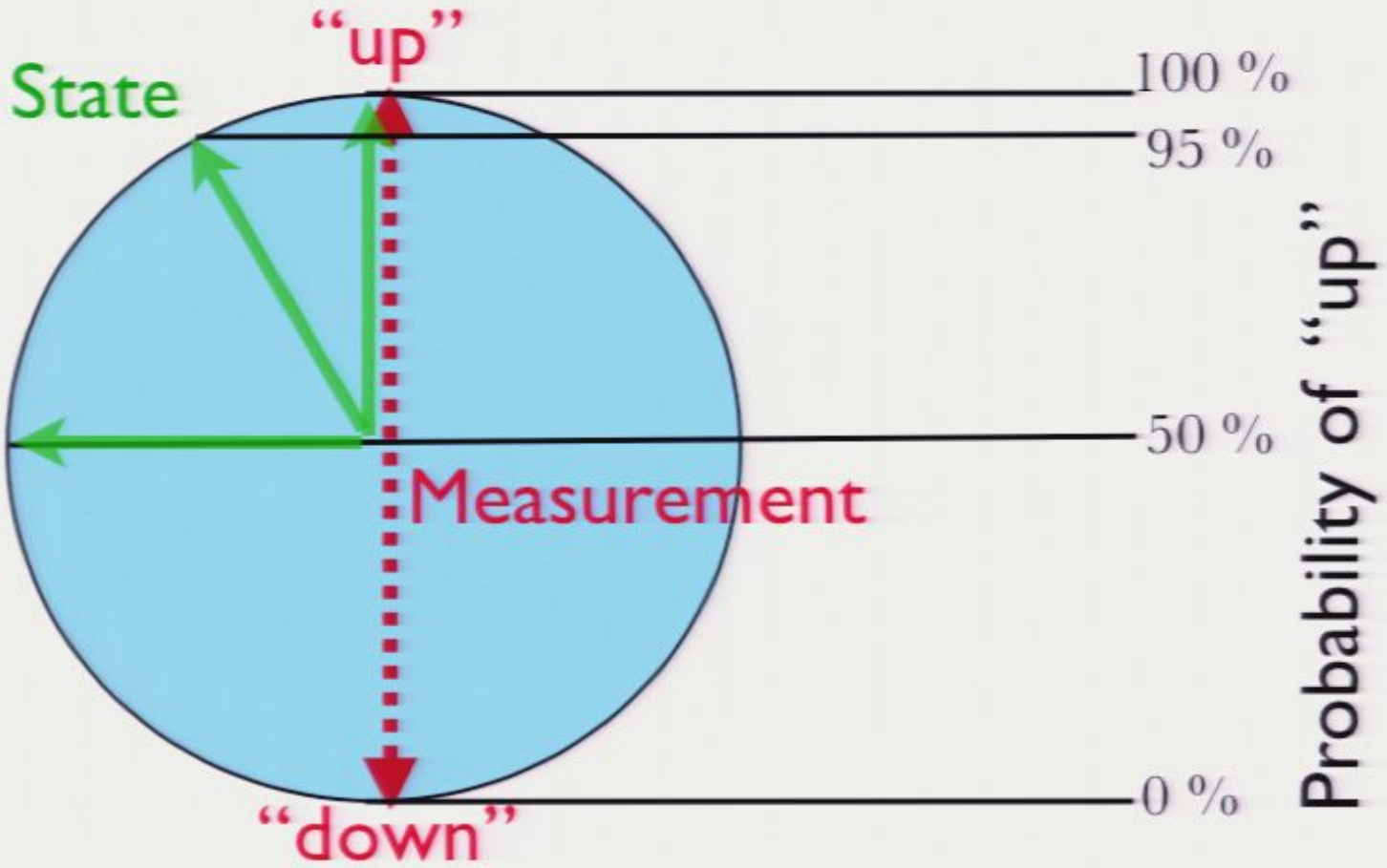

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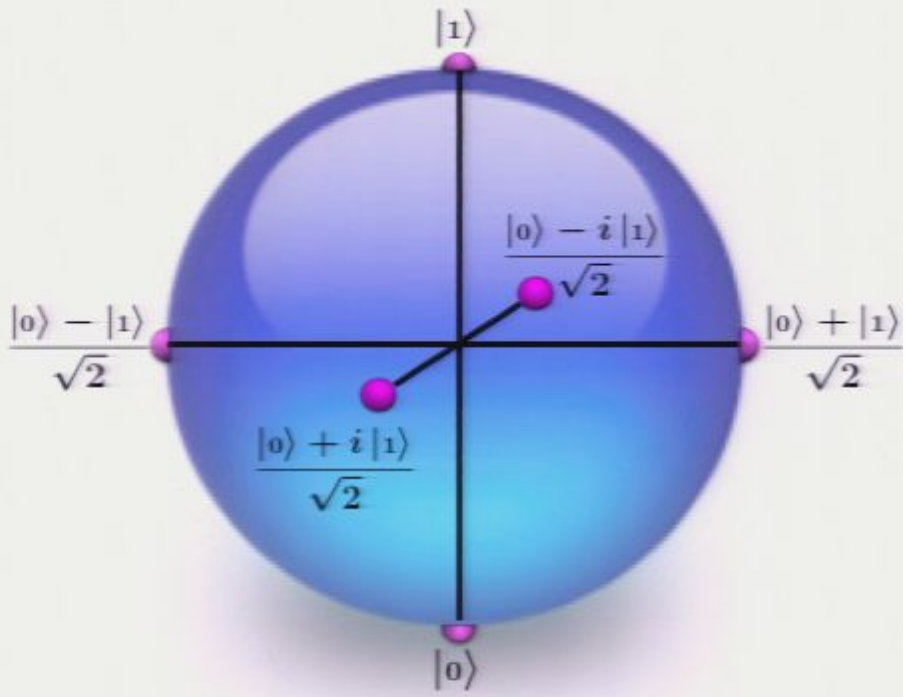

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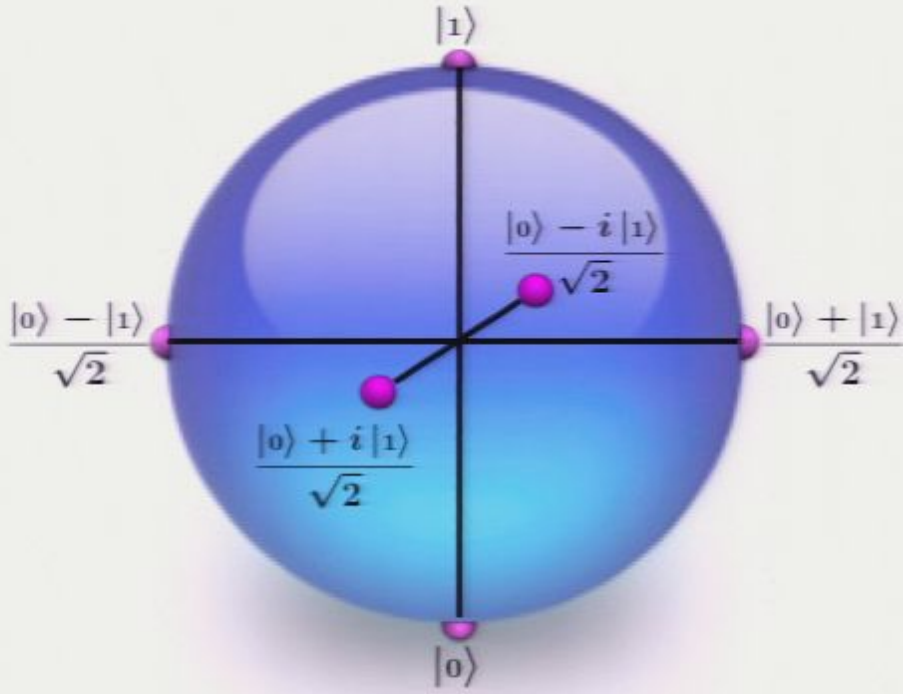

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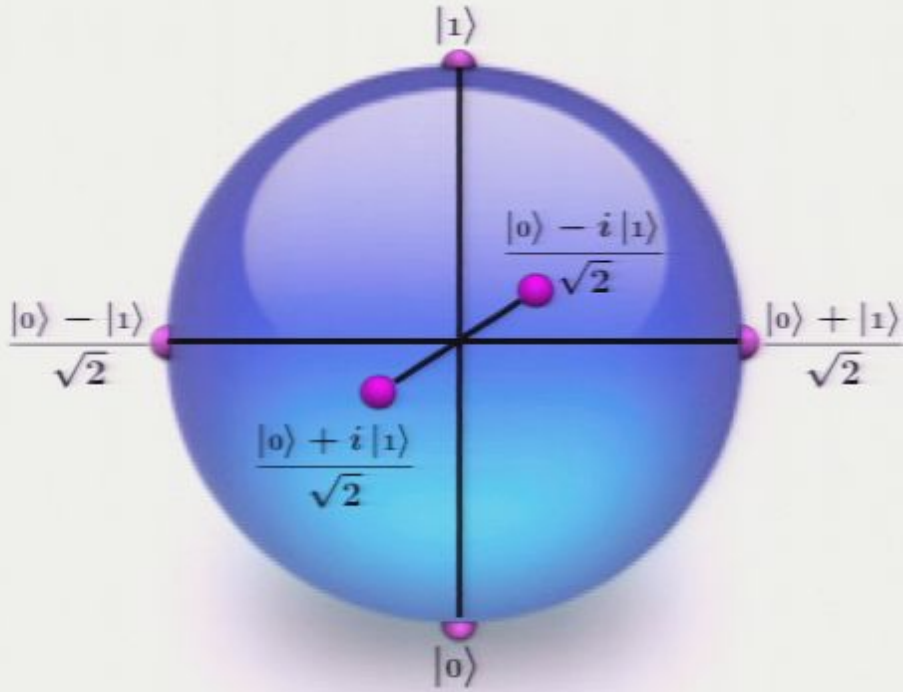

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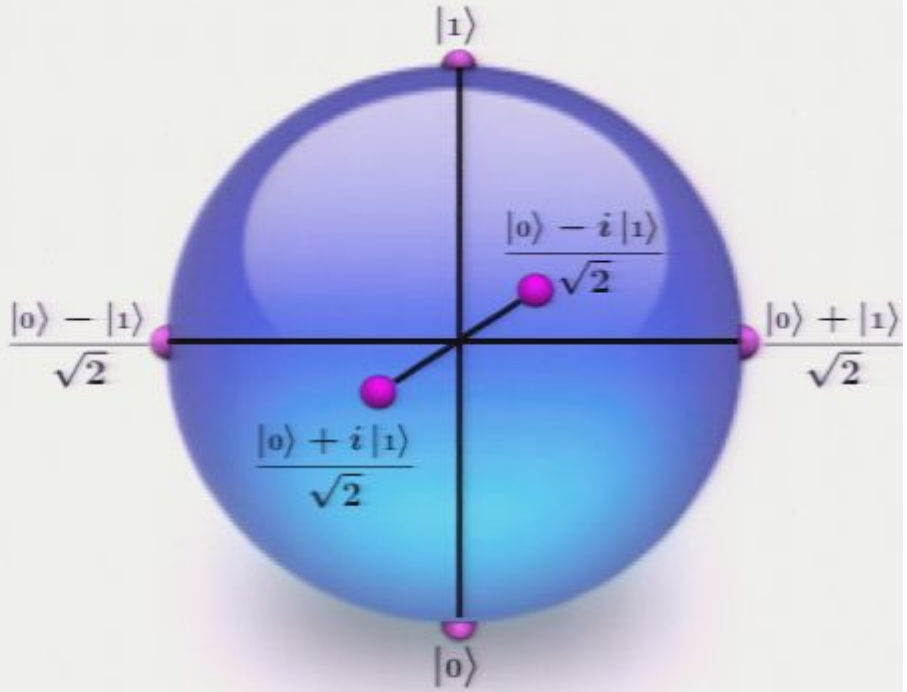

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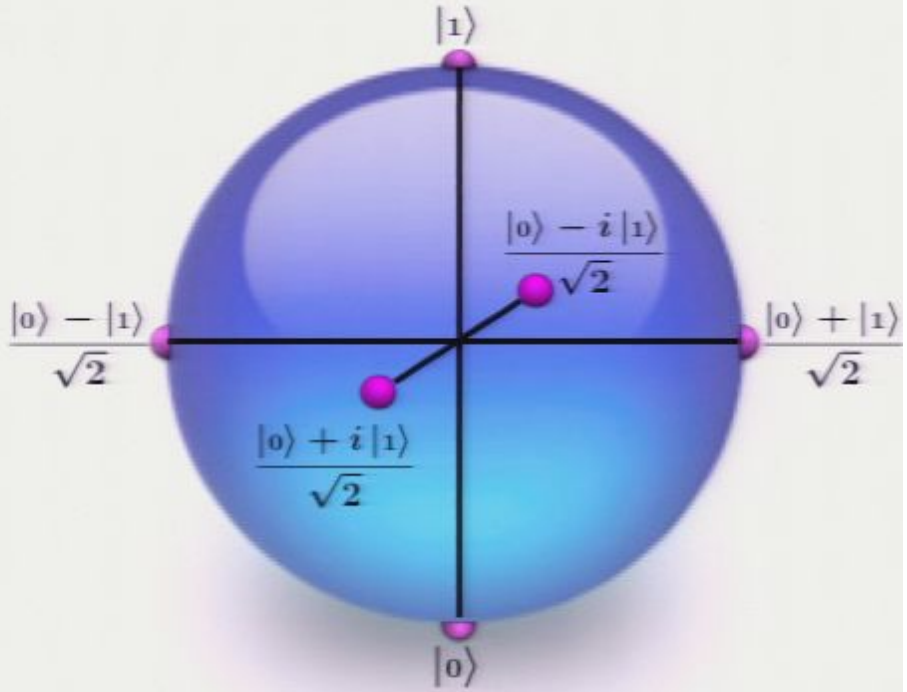

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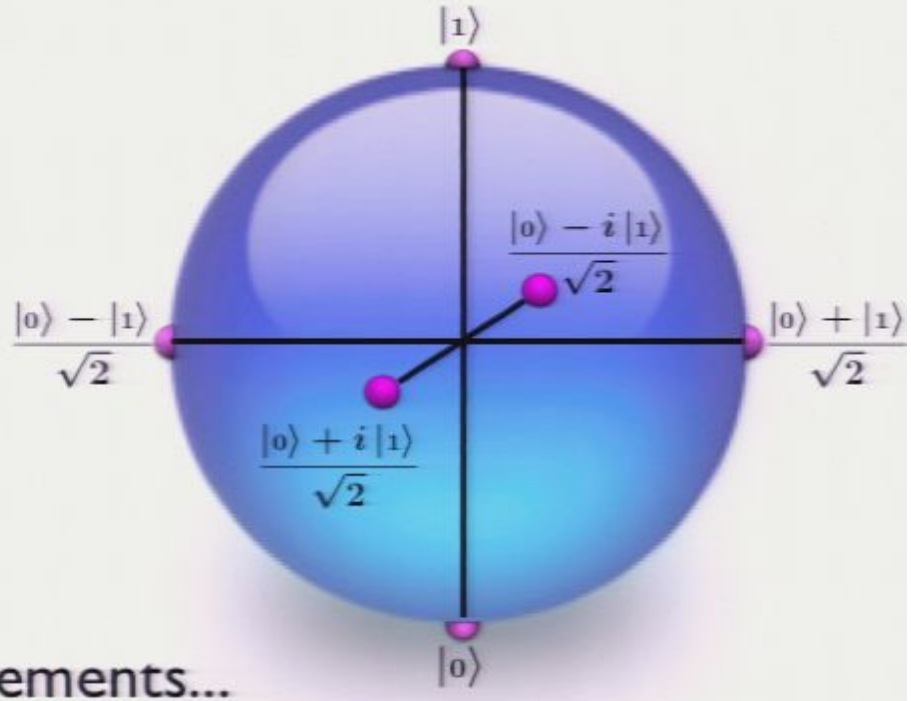

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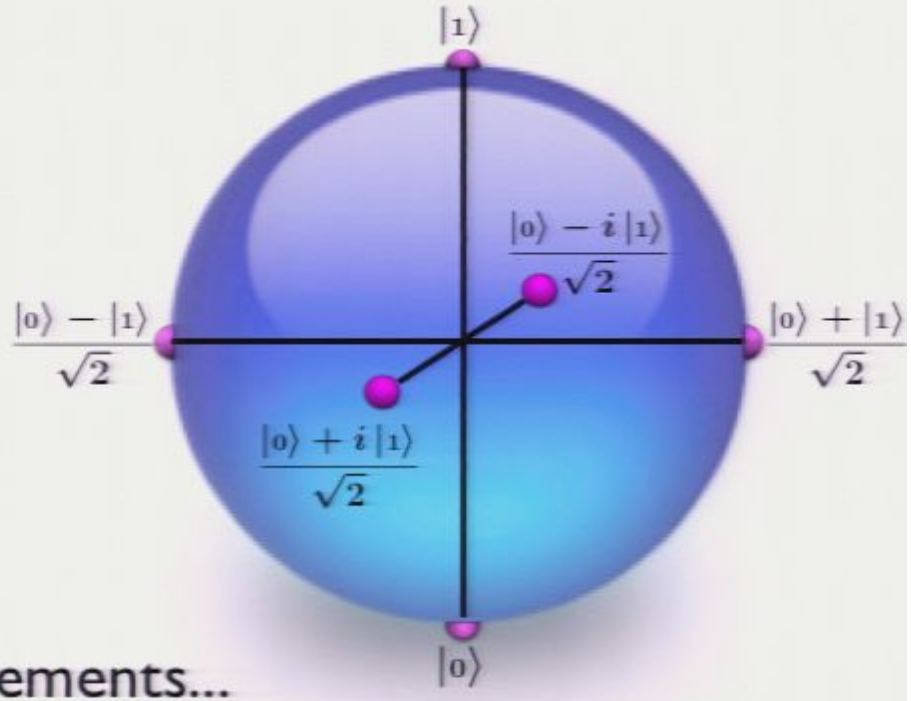

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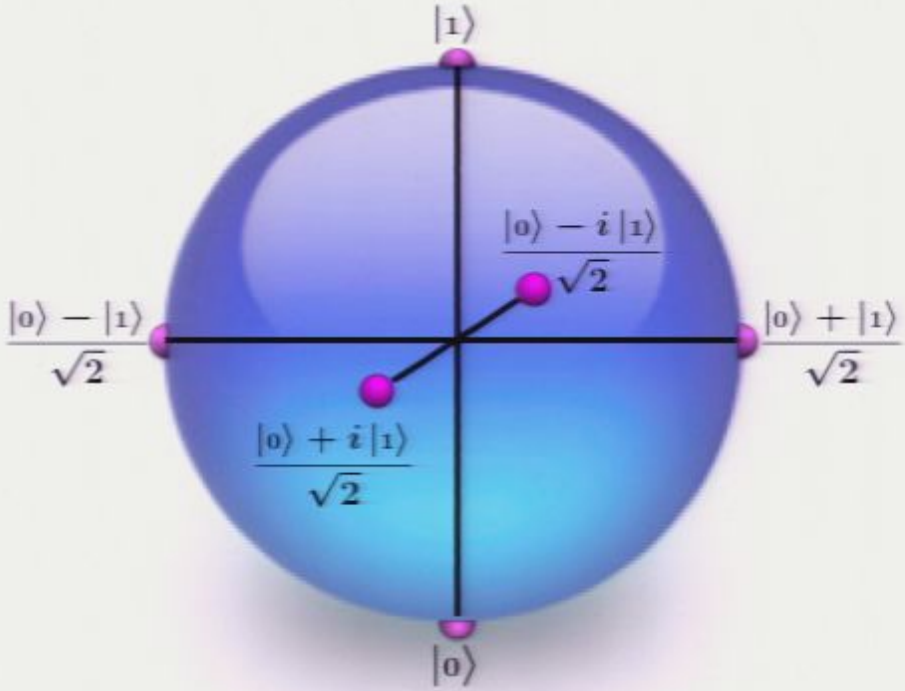
- If an Eavesdropper listens in, she *disturbs* the qubits... which Alice and Bob can detect by comparing some of their good bits.

Quantum Dynamics (for 1 qubit!)



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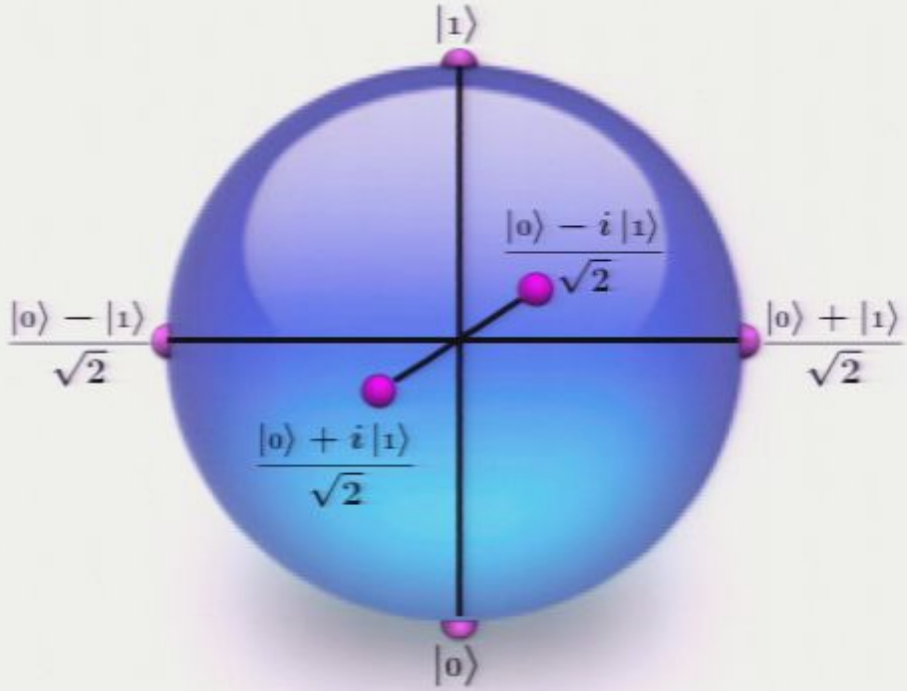

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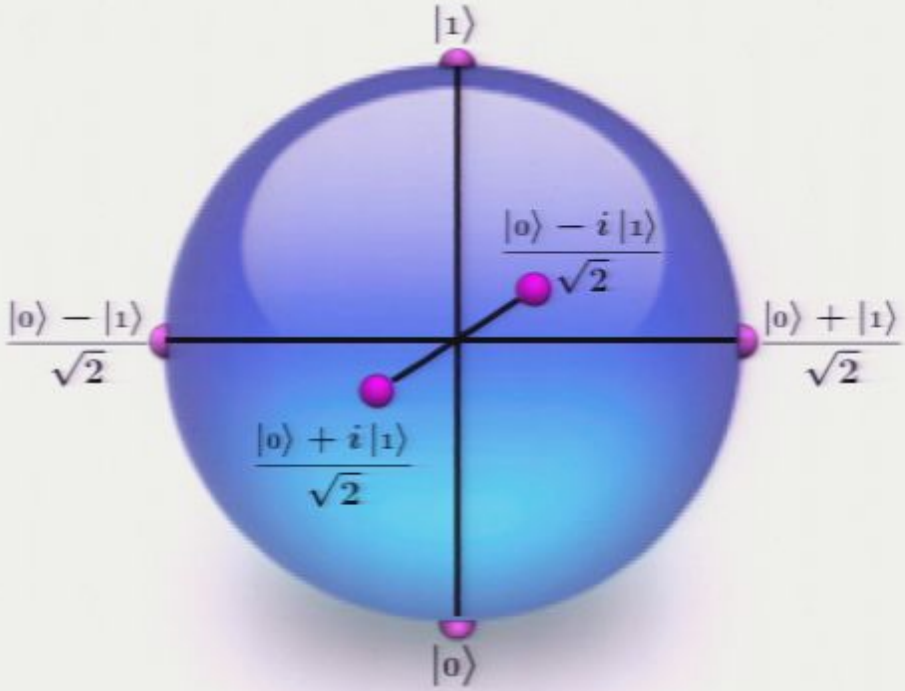

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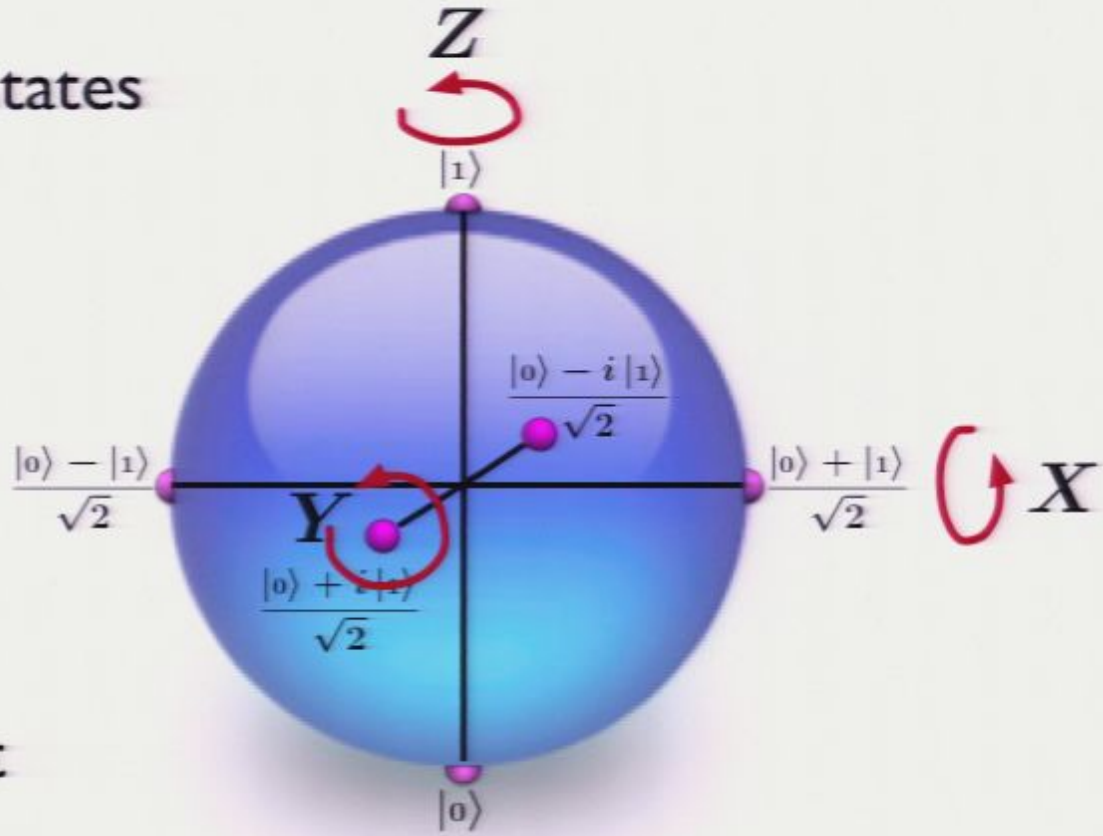

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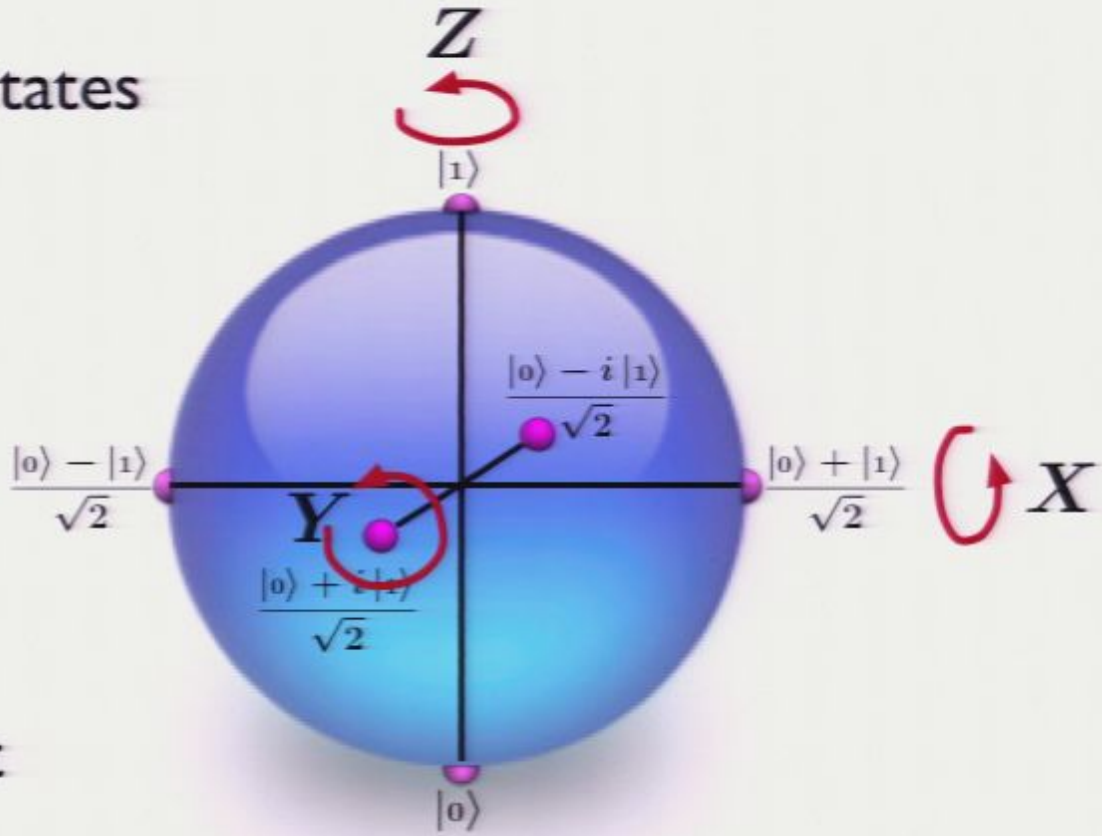

- There is a nice theorem about the Clifford group on systems of one **or** many qubits together...

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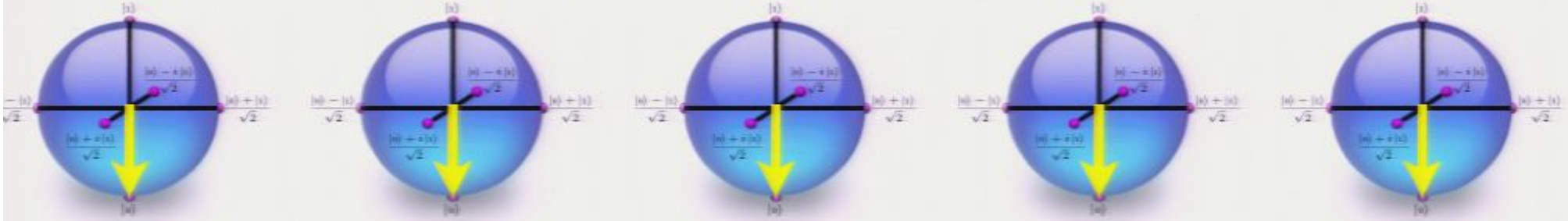
- Suppose we start with *N* qubits, each in the $|0\rangle$ state.



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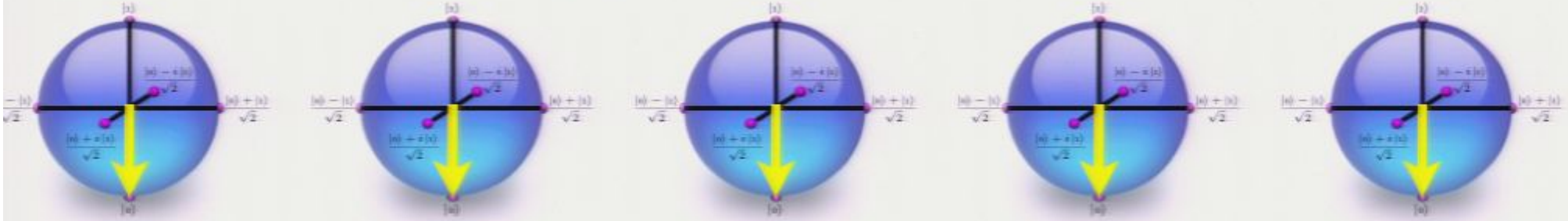

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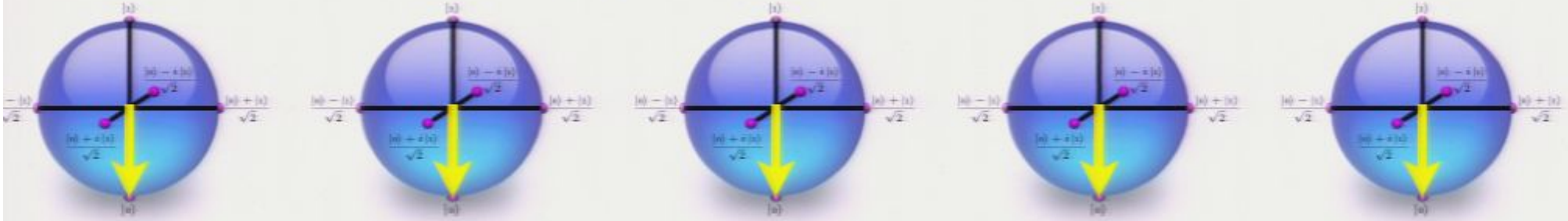

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...but why is this remarkable?...

Quantum Computation

- In general, dynamics of large quantum systems (e.g., *N* qubits) **can't** be simulated in less than $O(2^N)$ time by a classical computer. *Why?*

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- Feynman pointed out that a computer built of qubits could simulate quantum systems...
- ...so would such a device be more powerful than a classical computer?

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- Will a QC run regular software really fast? NO.


Ursus Mark IV, 1988


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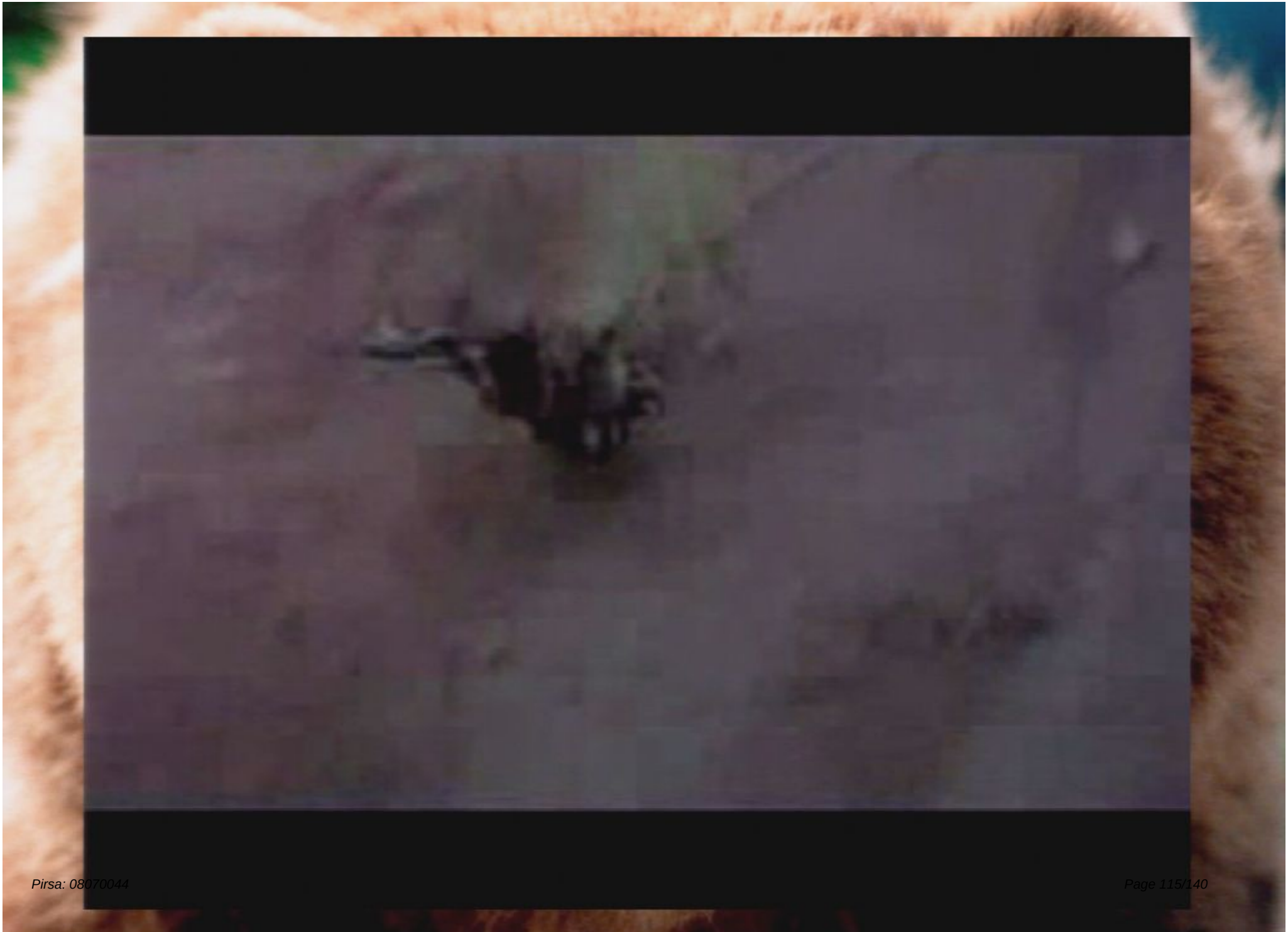
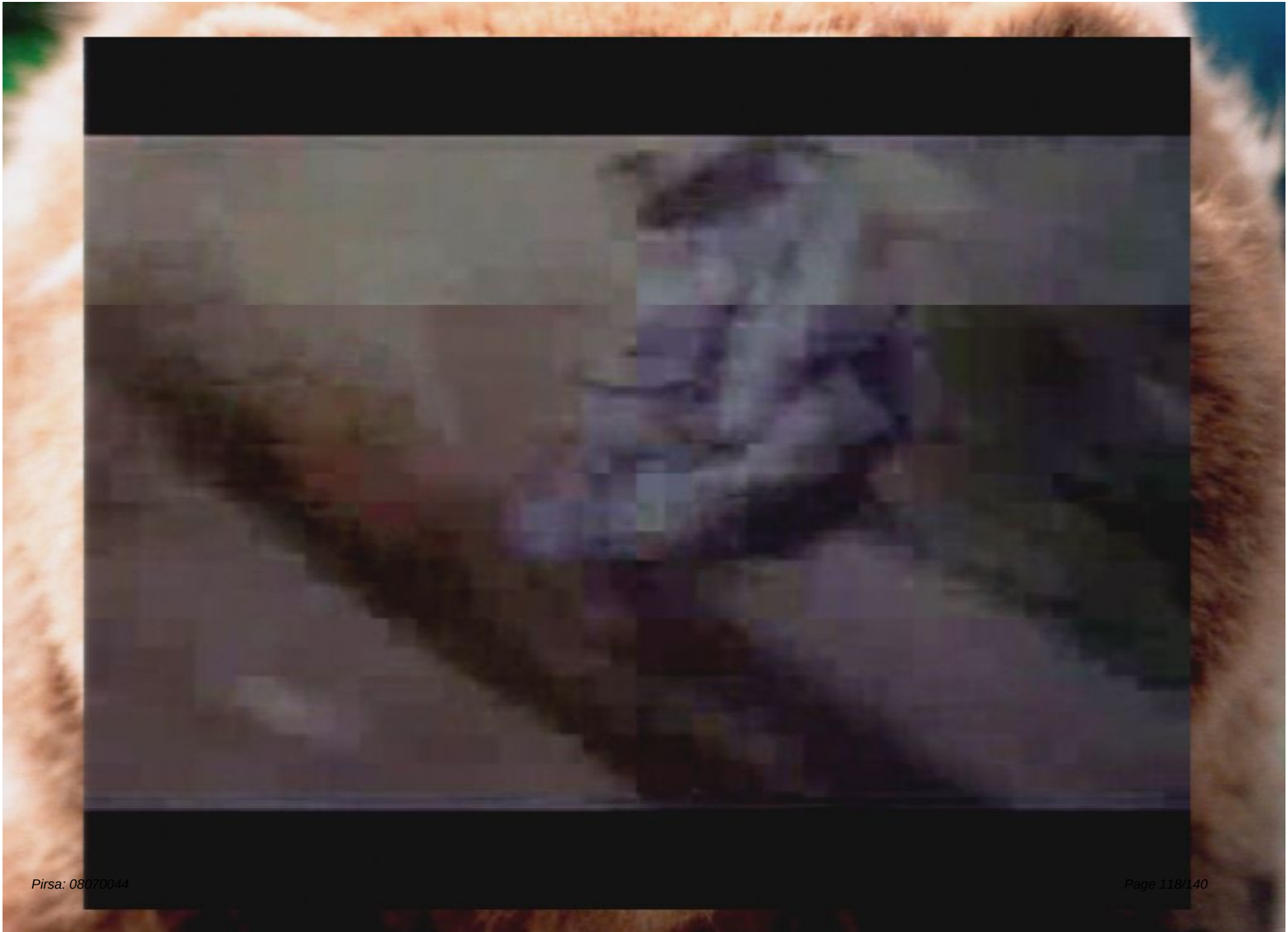
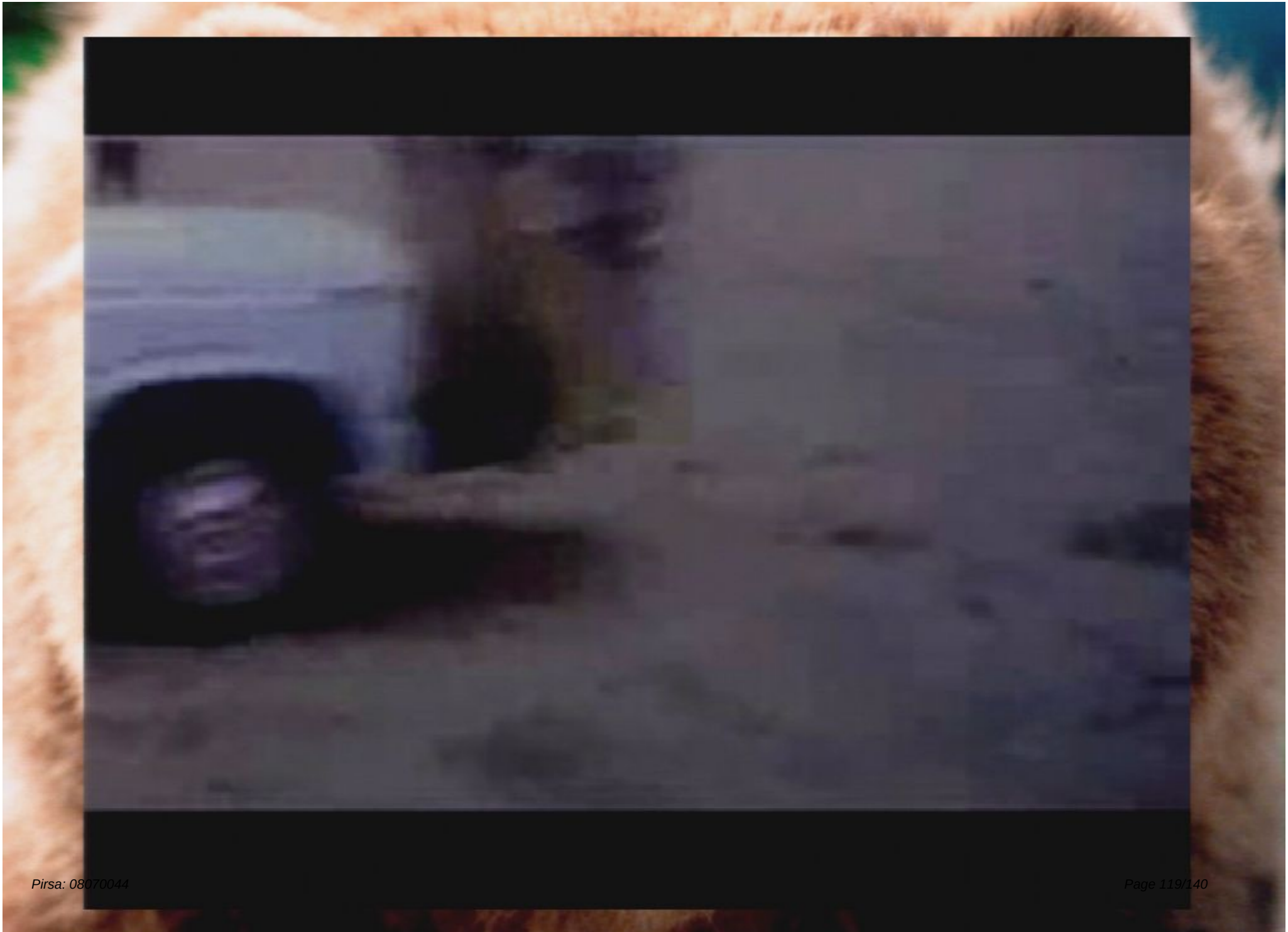
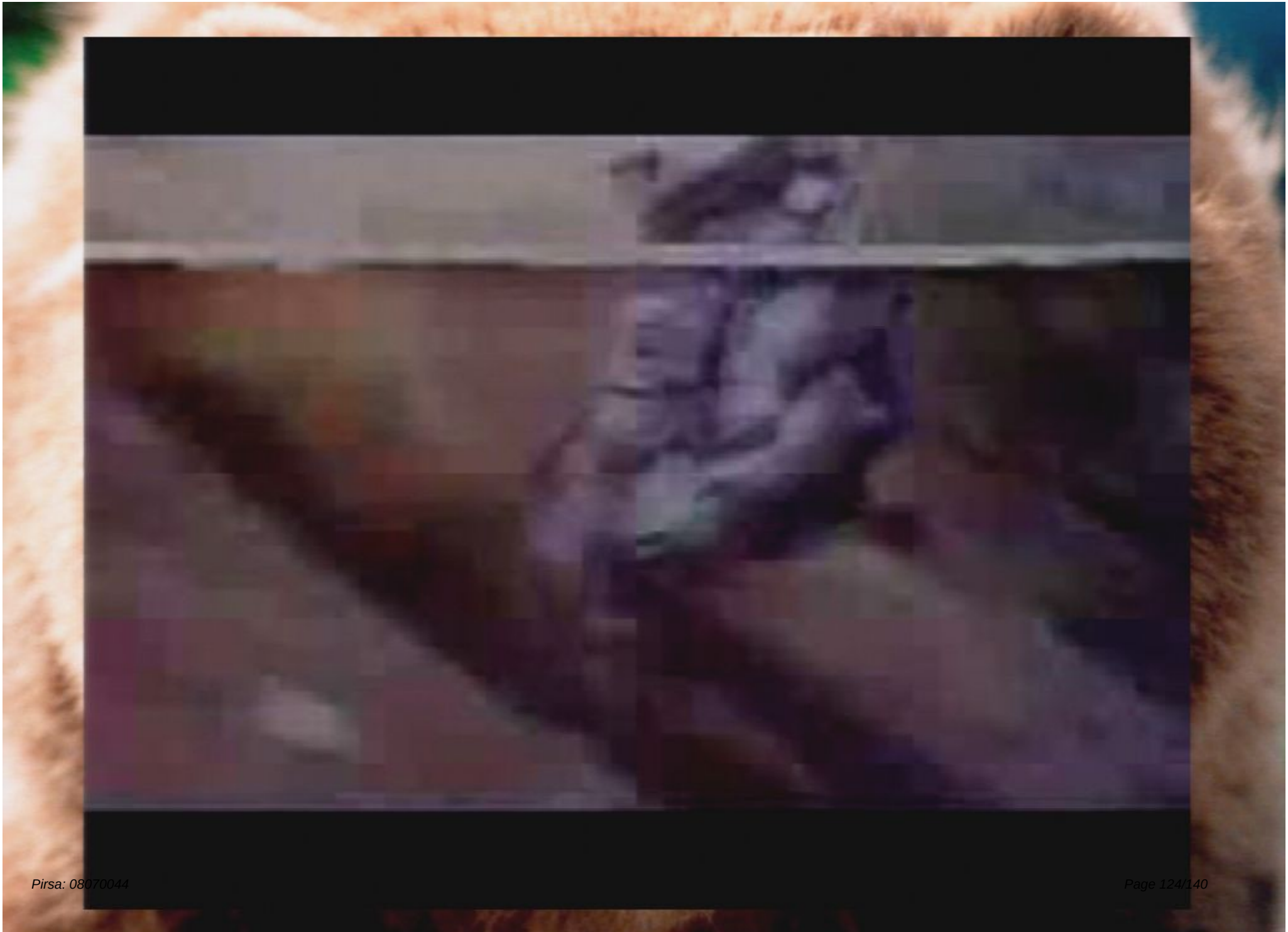
Ursus Mark V, Series A, 1989

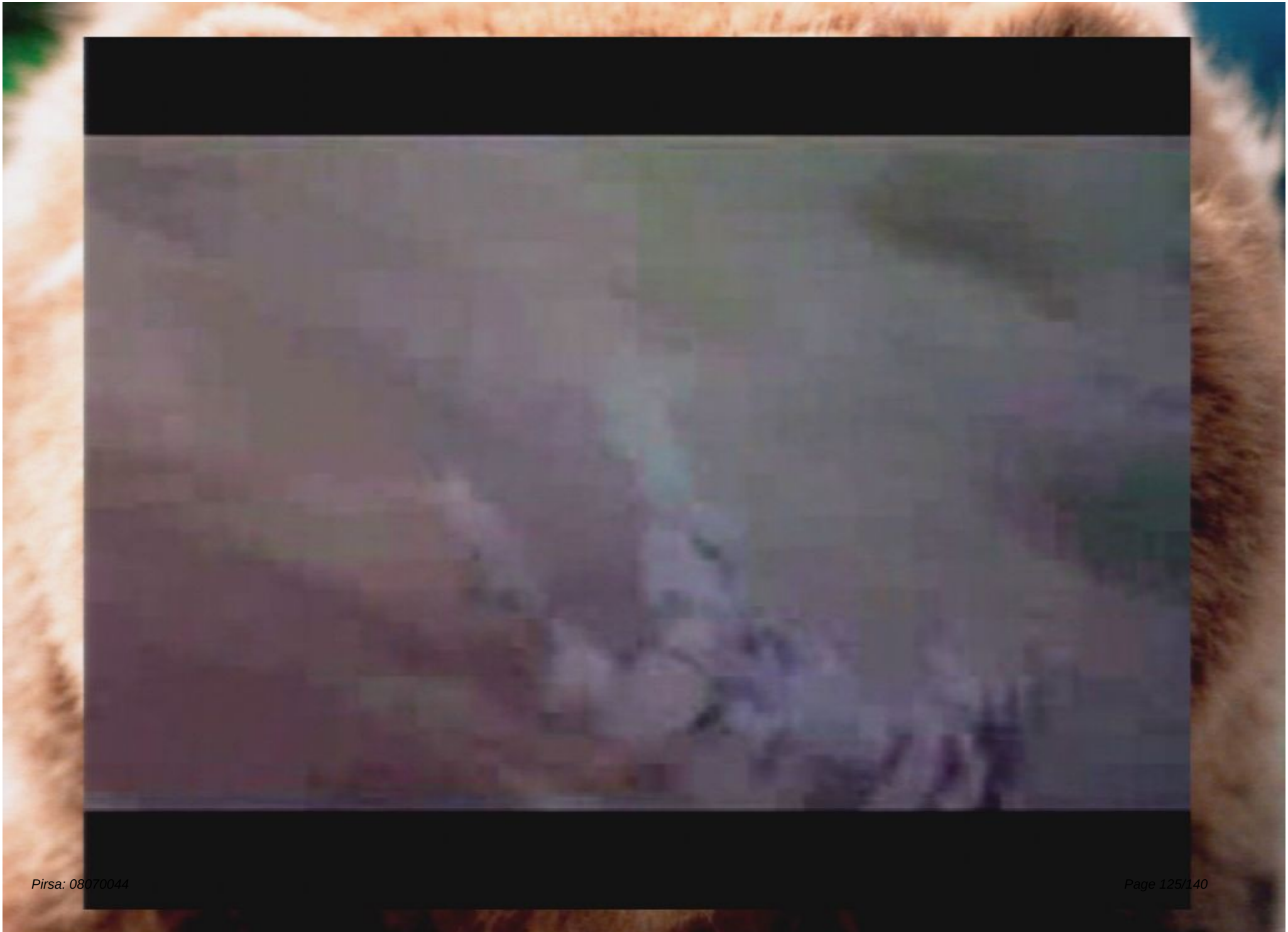

Niagara Escarpment, 1989
Hamilton, Ontario

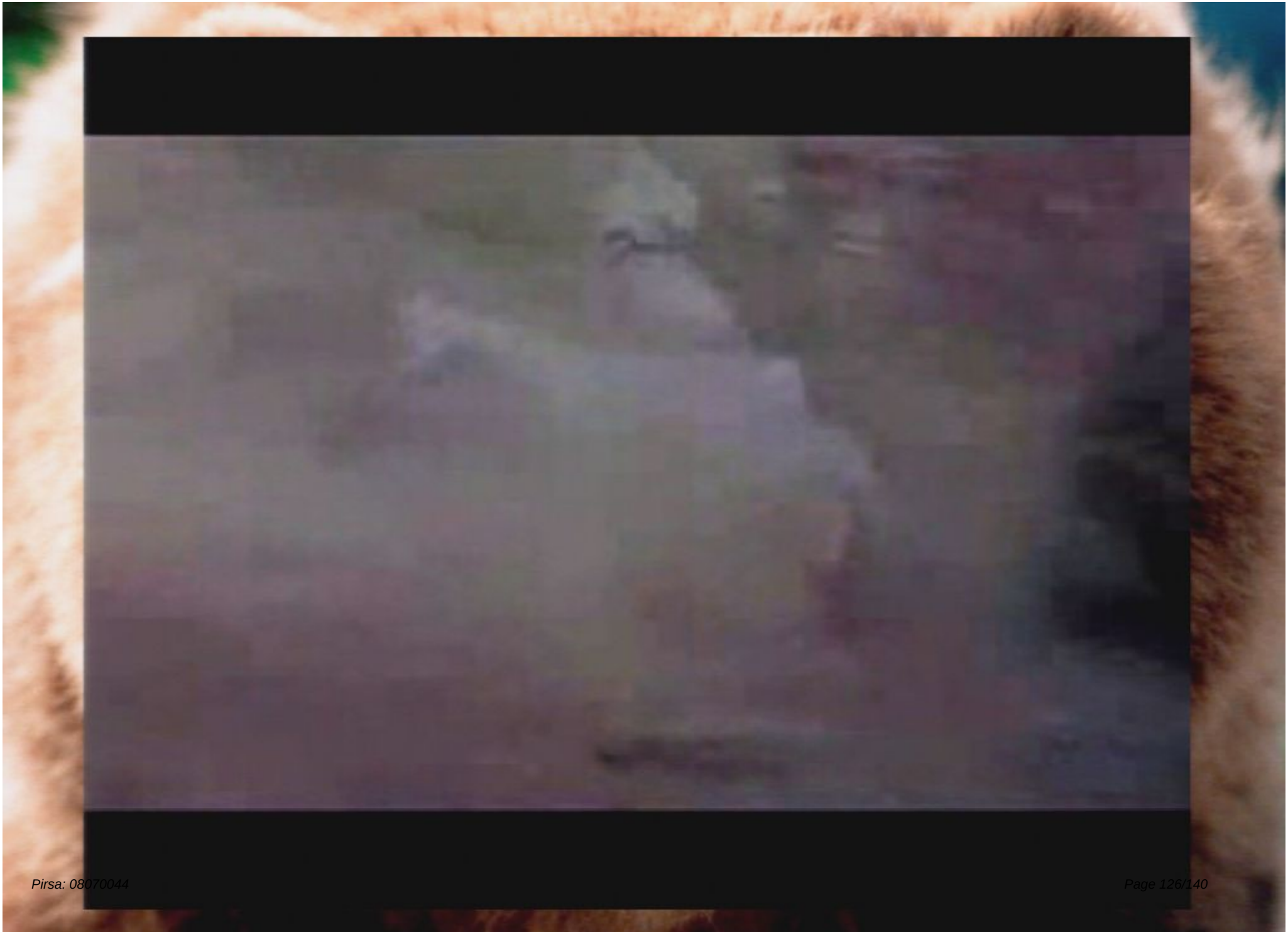


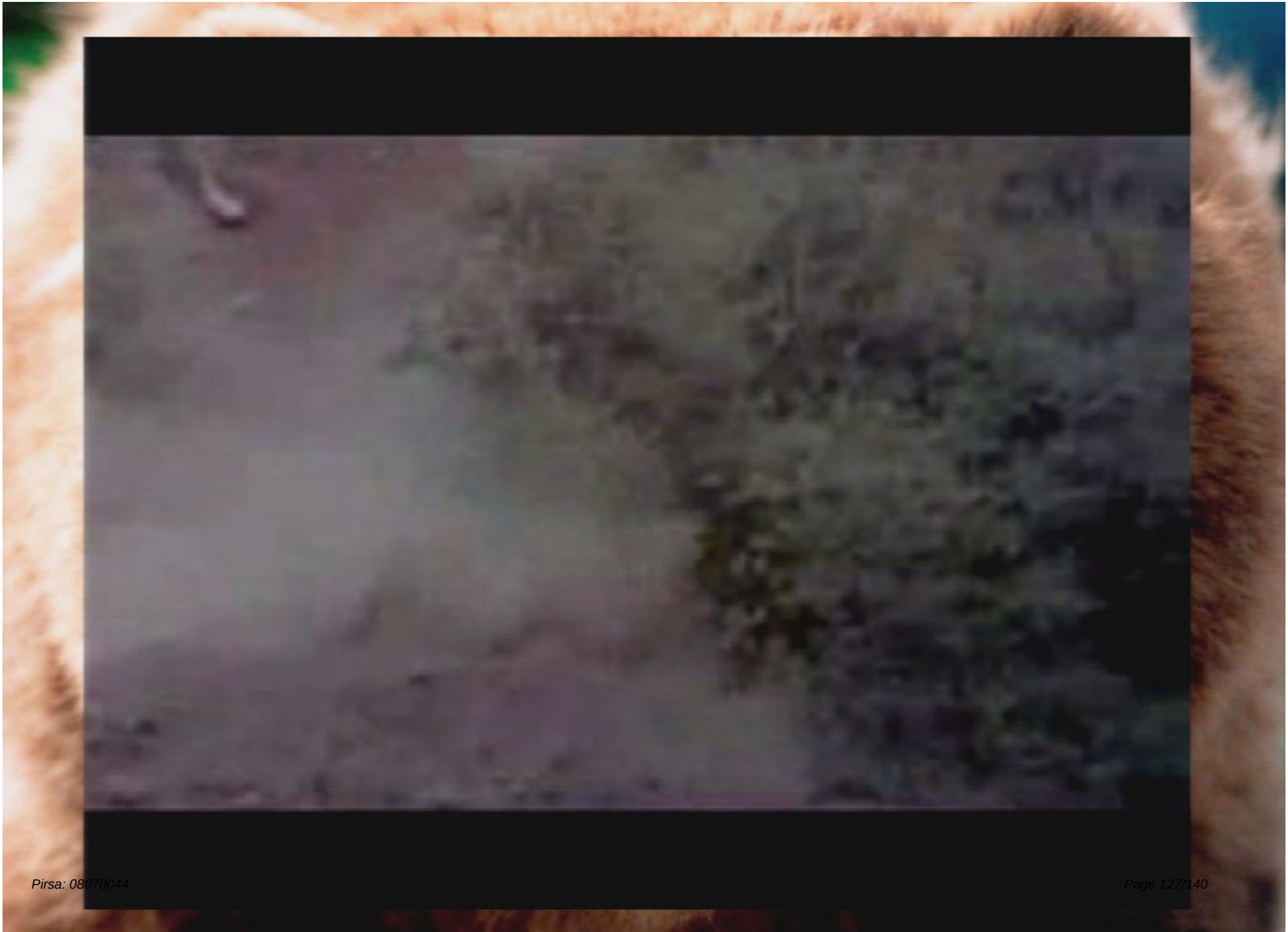








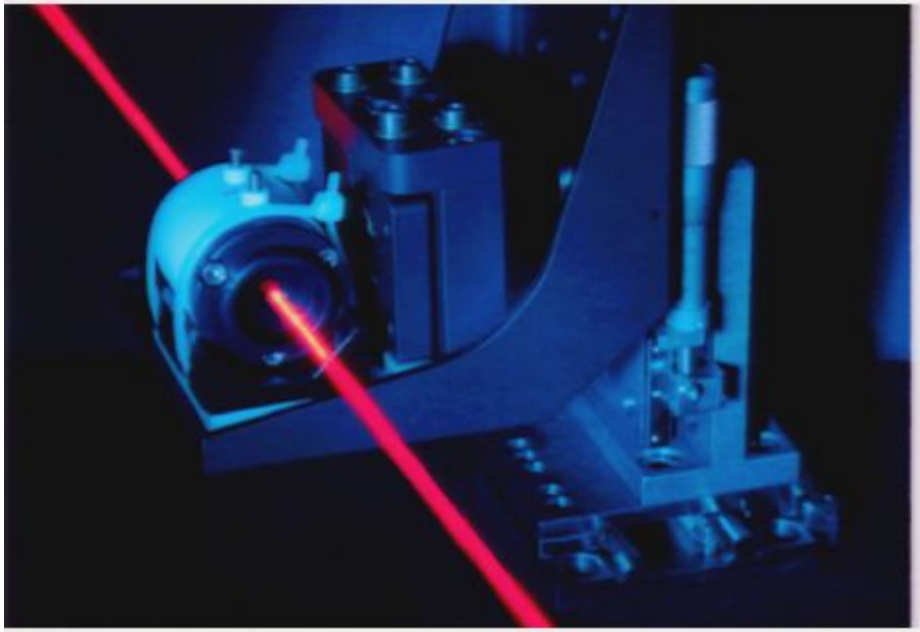


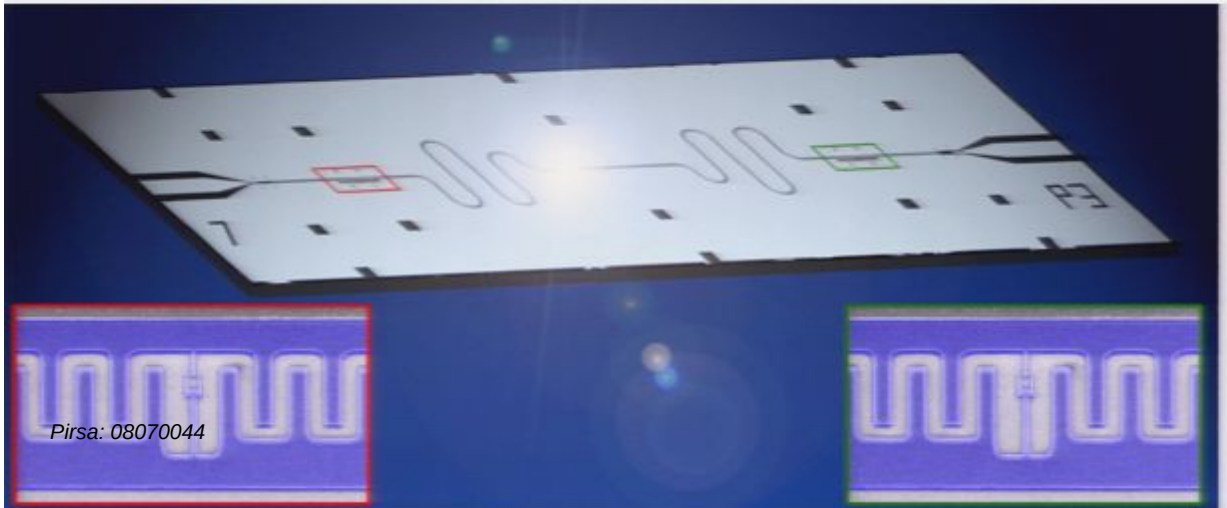


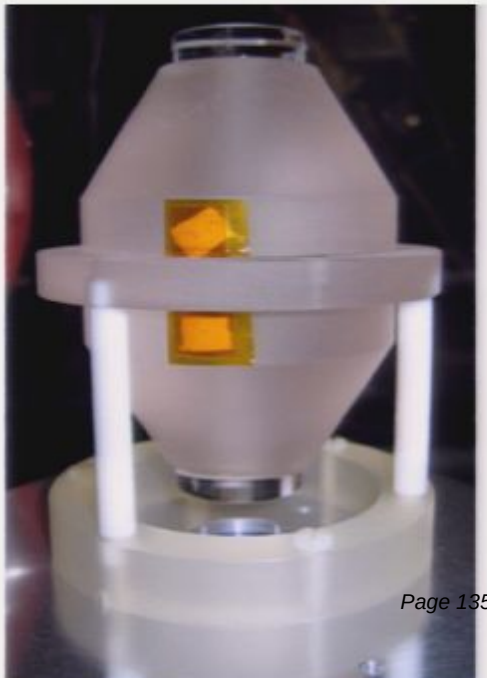
The Science:
Quantum Info in the Lab

The Science: Quantum Info in the Lab

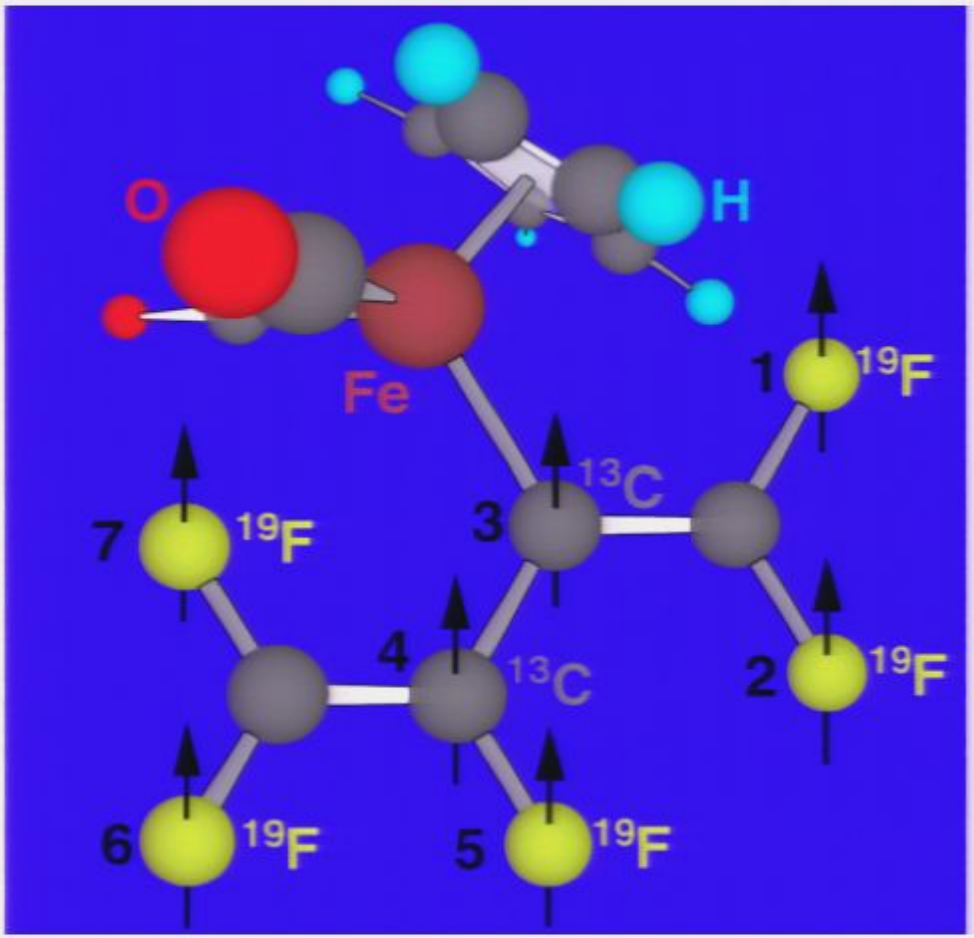
Photons: the ideal qubit





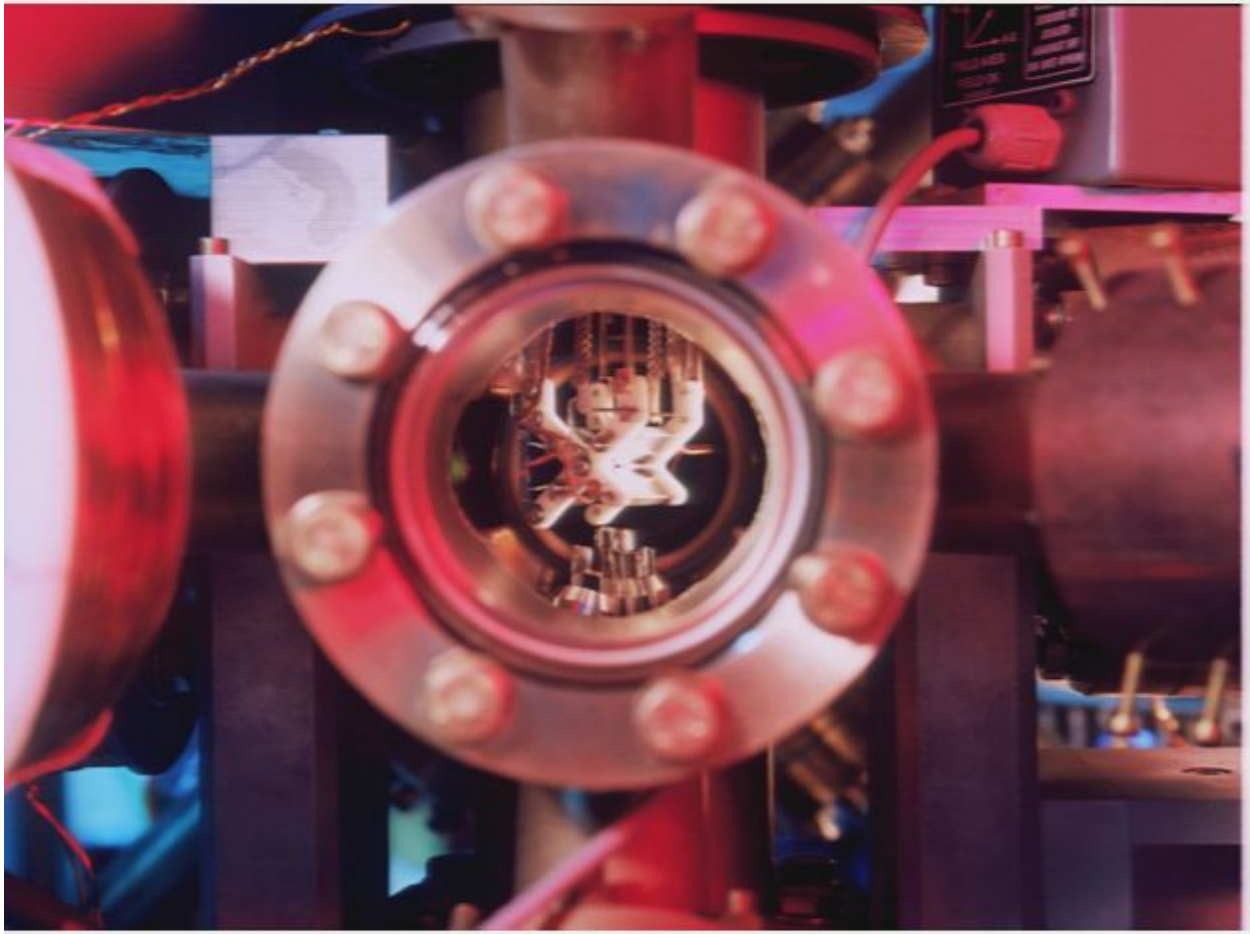


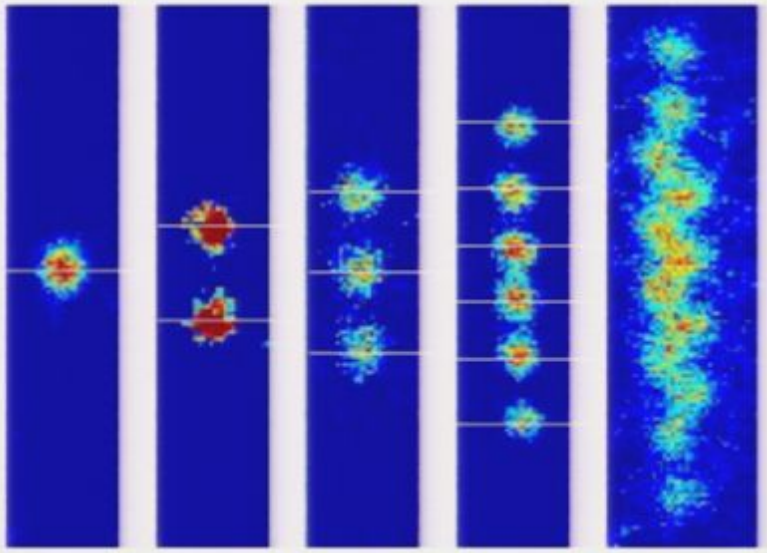
Nuclear Magnetic Resonance: here today, gone tomorrow

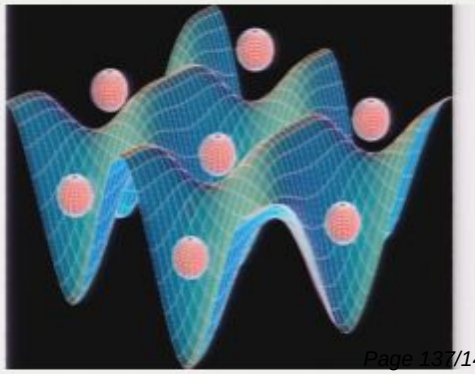


NMR QC (5-bit)

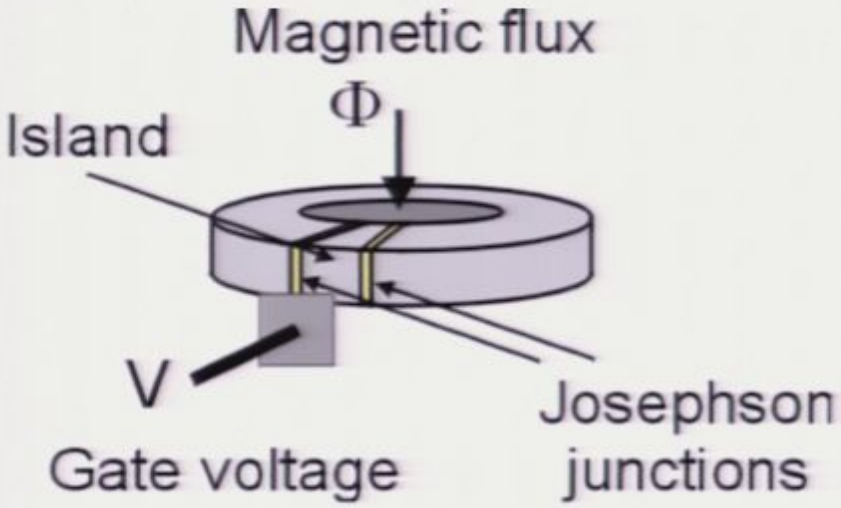
Atoms & Ions: precise control

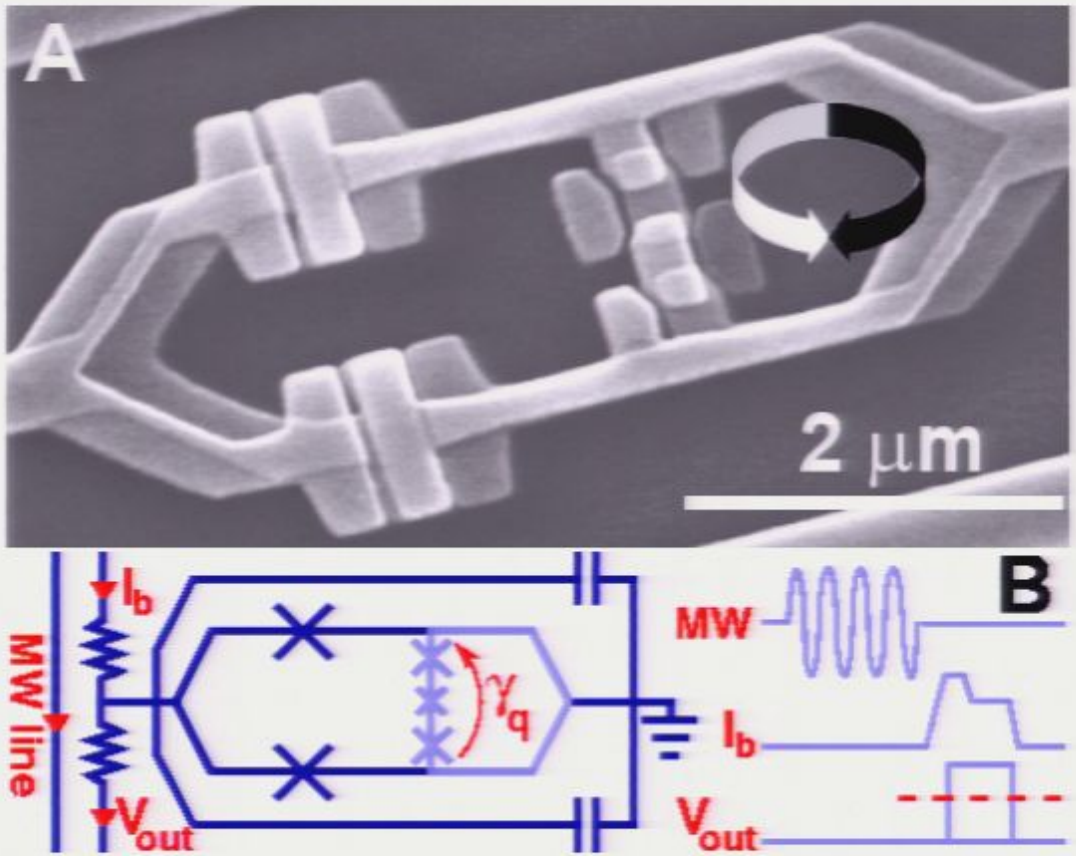






SQUIDs: technology of tomorrow?





Research Fronts

- Quantum error-correcting codes
- Fault-tolerant quantum computation
- Novel models of quantum computing
  - adiabatic QC
  - measurement-based "single-use" QC
  - topological QC
- What is QM a theory **of**? Reality? or knowledge?
- Where does the power of QC come from?
- Designing new quantum algorithms
- Decoherence: why does the world look classical?