

Title: Keynote Presentation - Harnessing the Quantum World

Date: Jul 26, 2006 09:00 AM

URL: <http://pirsa.org/06070073>

Abstract:

Harnessing the Quantum World



Harnessing the Quantum World



Plan

- Why quantum information?
- What is quantum computing?
- Steps towards building these devices.

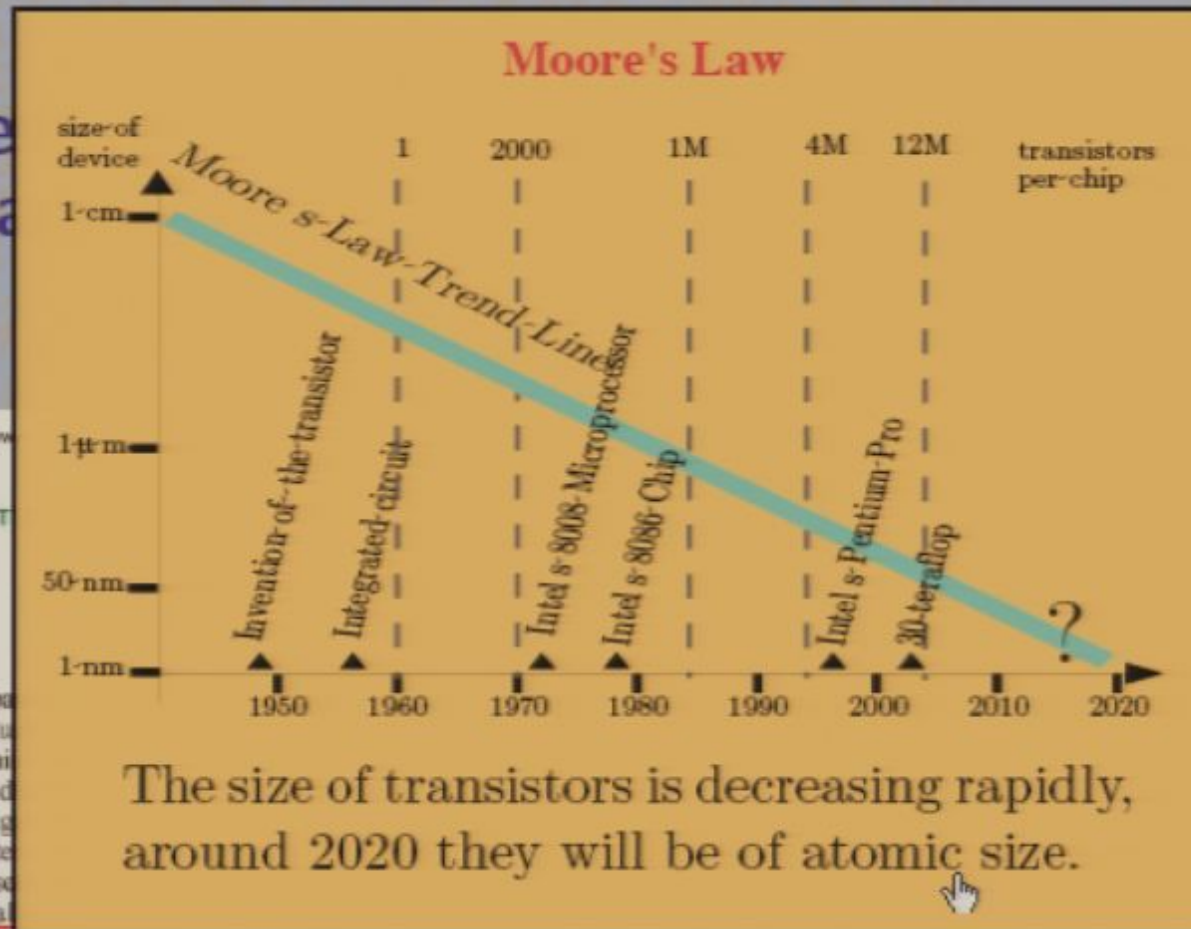


Information Processing Devices



Why Quant. Info. Processing?

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PERSPECT

For the past few decades, the semiconductor industry has followed Moore's law, which states that the number of transistors on a chip doubles every two years. But now it seems that this trend is coming to an end. Fundamental physical limits are being reached in critical areas, and unless new, innovative solutions are found, the current rate of improvement cannot be maintained.

The dominant electronic device used today in integrated circuits is the silicon-

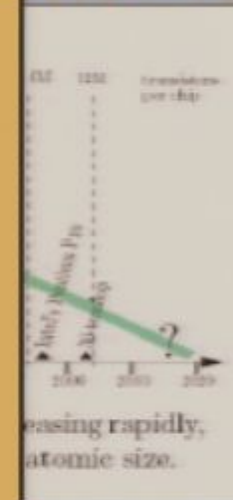
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References

1. G. Moore, IEDM Tech. Dig. (1975), p. 11.
2. R. H. Tienard et al., IEEE J. Solid-State Circuits, SC-9.

concentration of these donor and acceptor atoms to maintain a constant total charge

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Hardware

find wall for Moore's Law

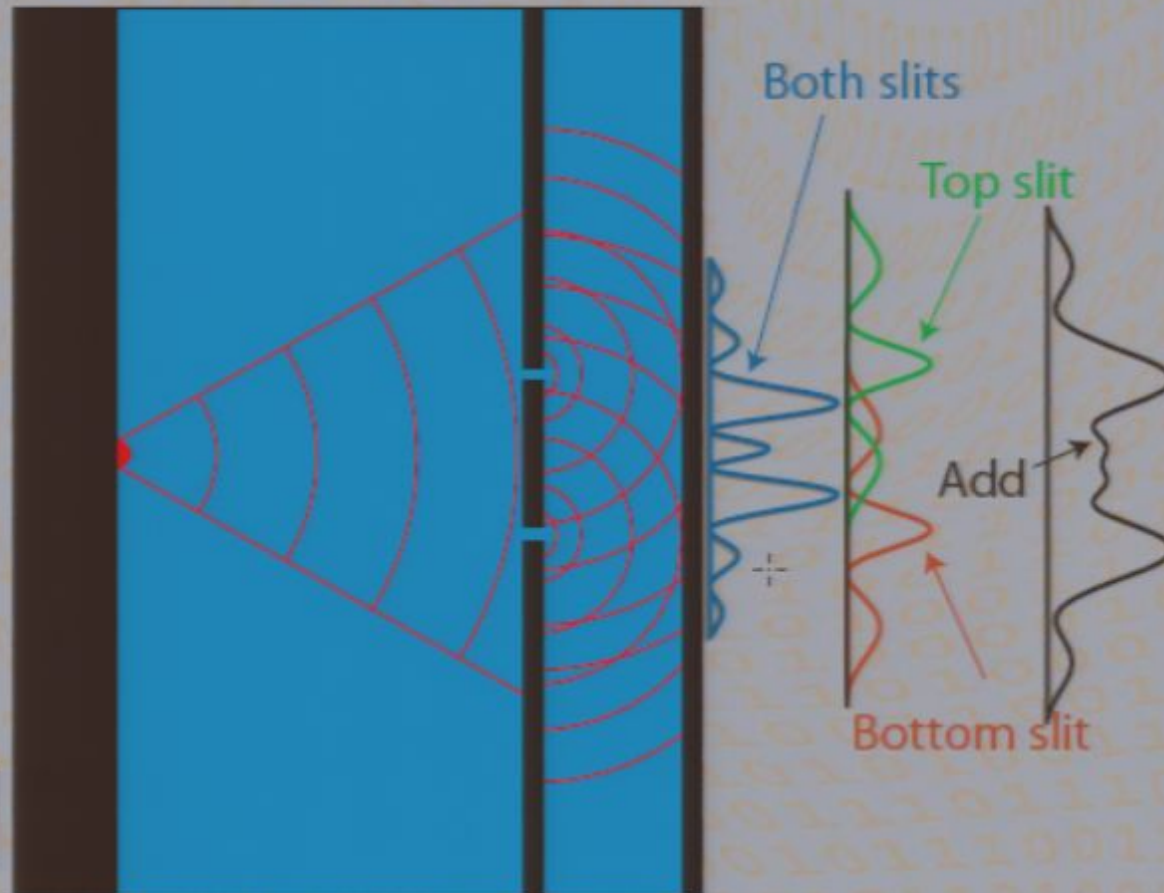
manipulators generally refer to it today, according to a recent research paper.

won't come for about two decades, but Intel has published a paper theorizing that it will when it comes to shrinking the size of the methods for making chips that are faster and cheaper than their predecessors.

manipulators will be able to produce chips on the 16-nanometer manufacturing process, expected by conservative estimates to arrive in 2018, and maybe one or two manufacturing processes after that, but that's it.

Basics of Quantum Mechanics

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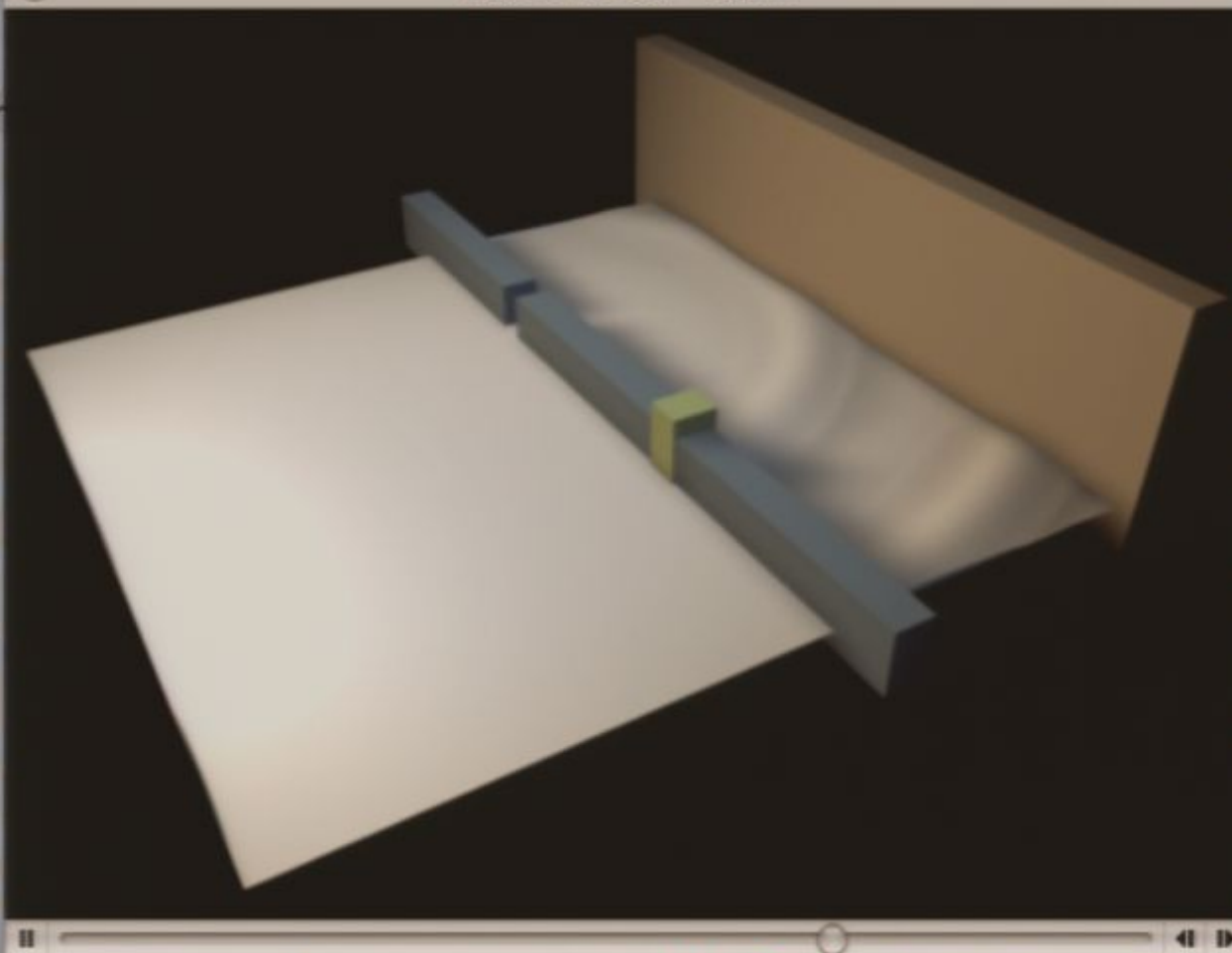


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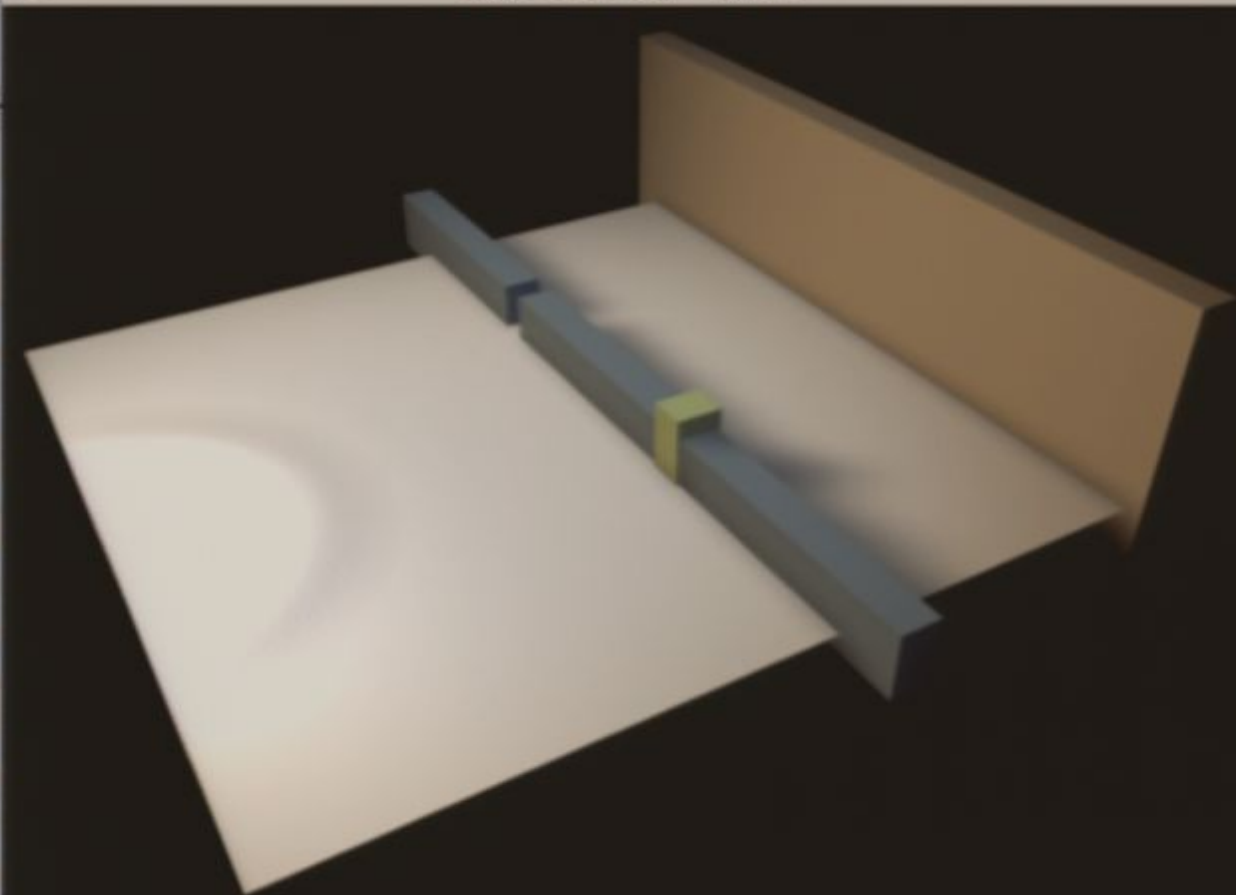


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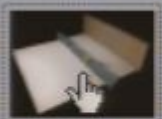
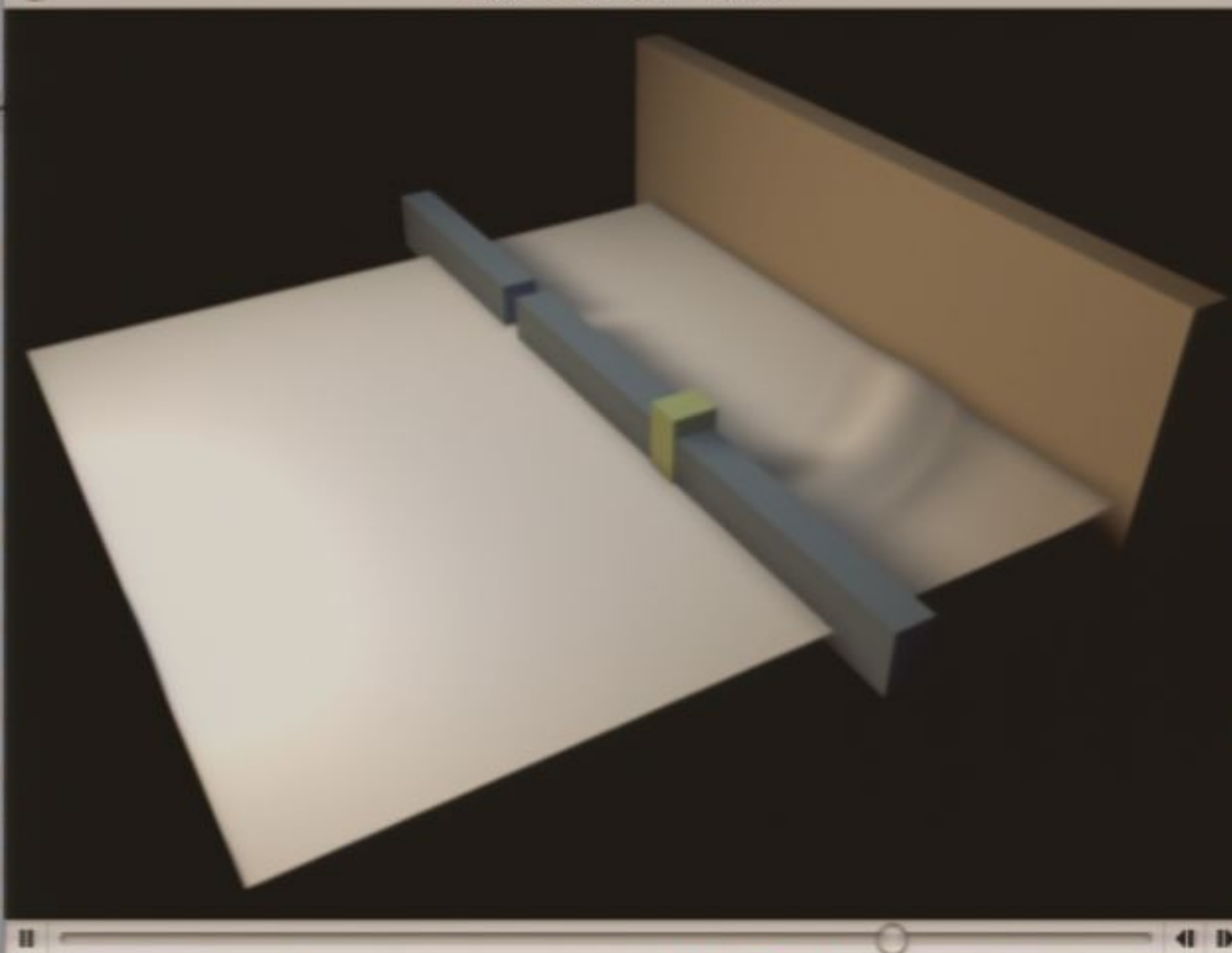


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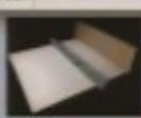
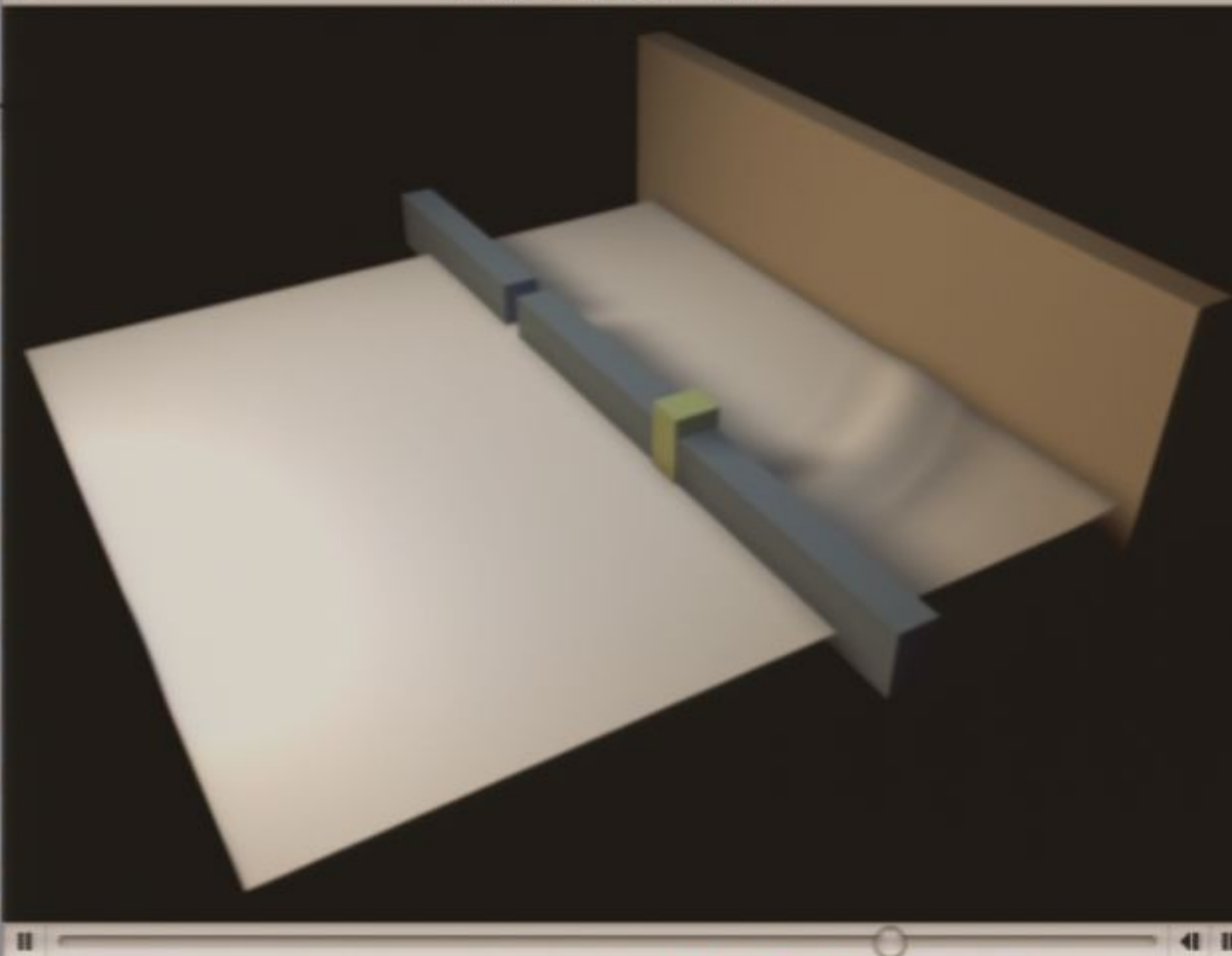


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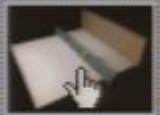
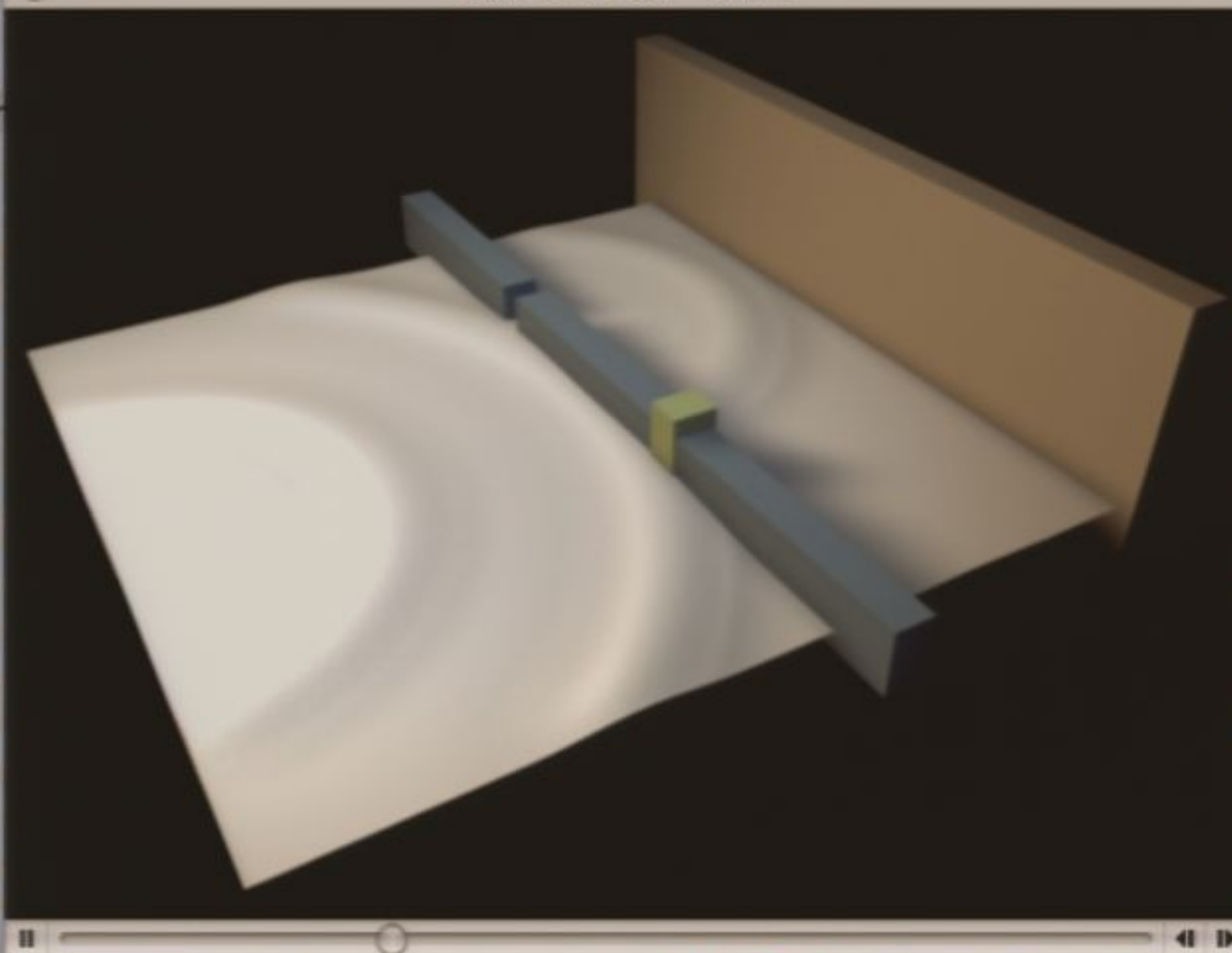


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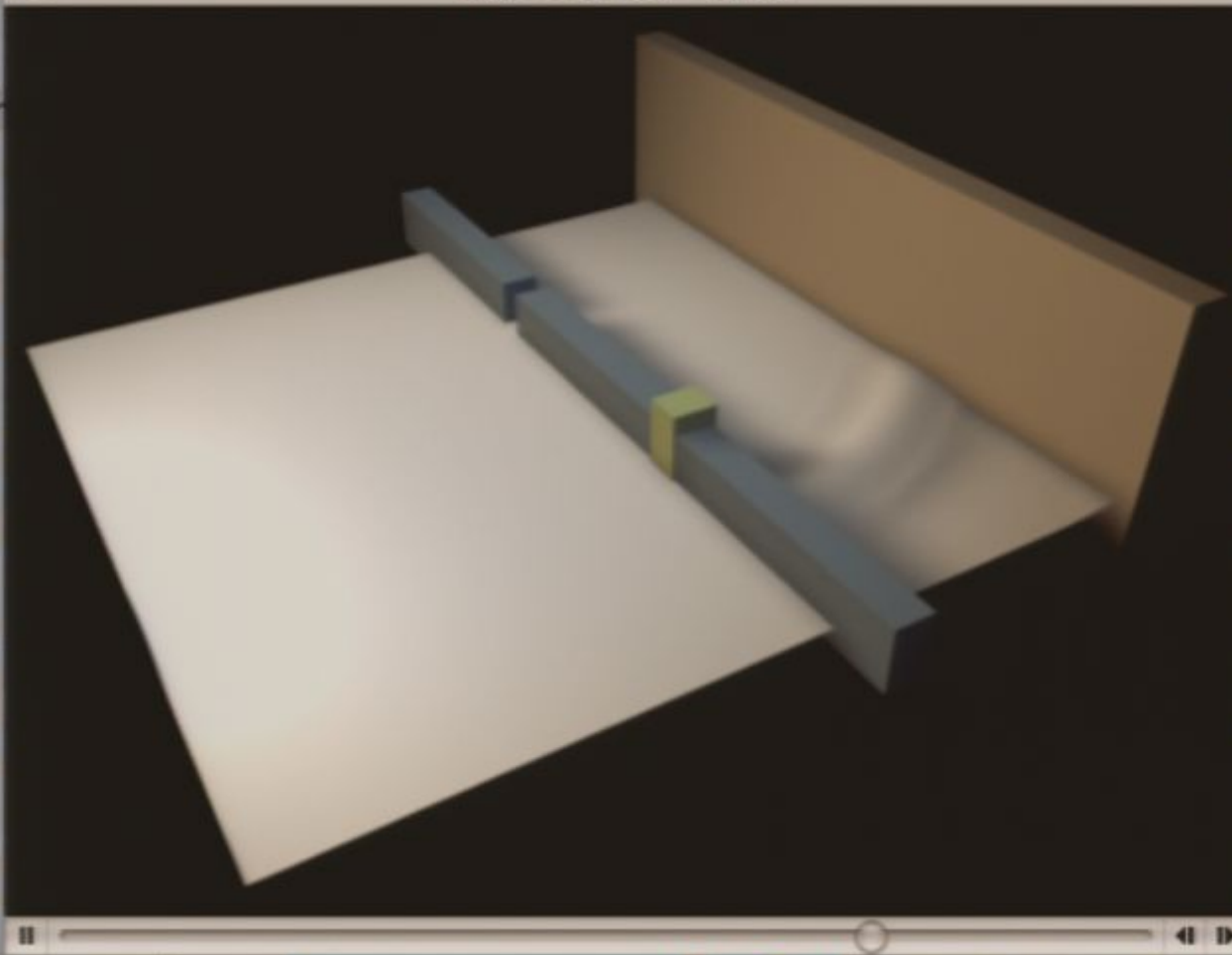


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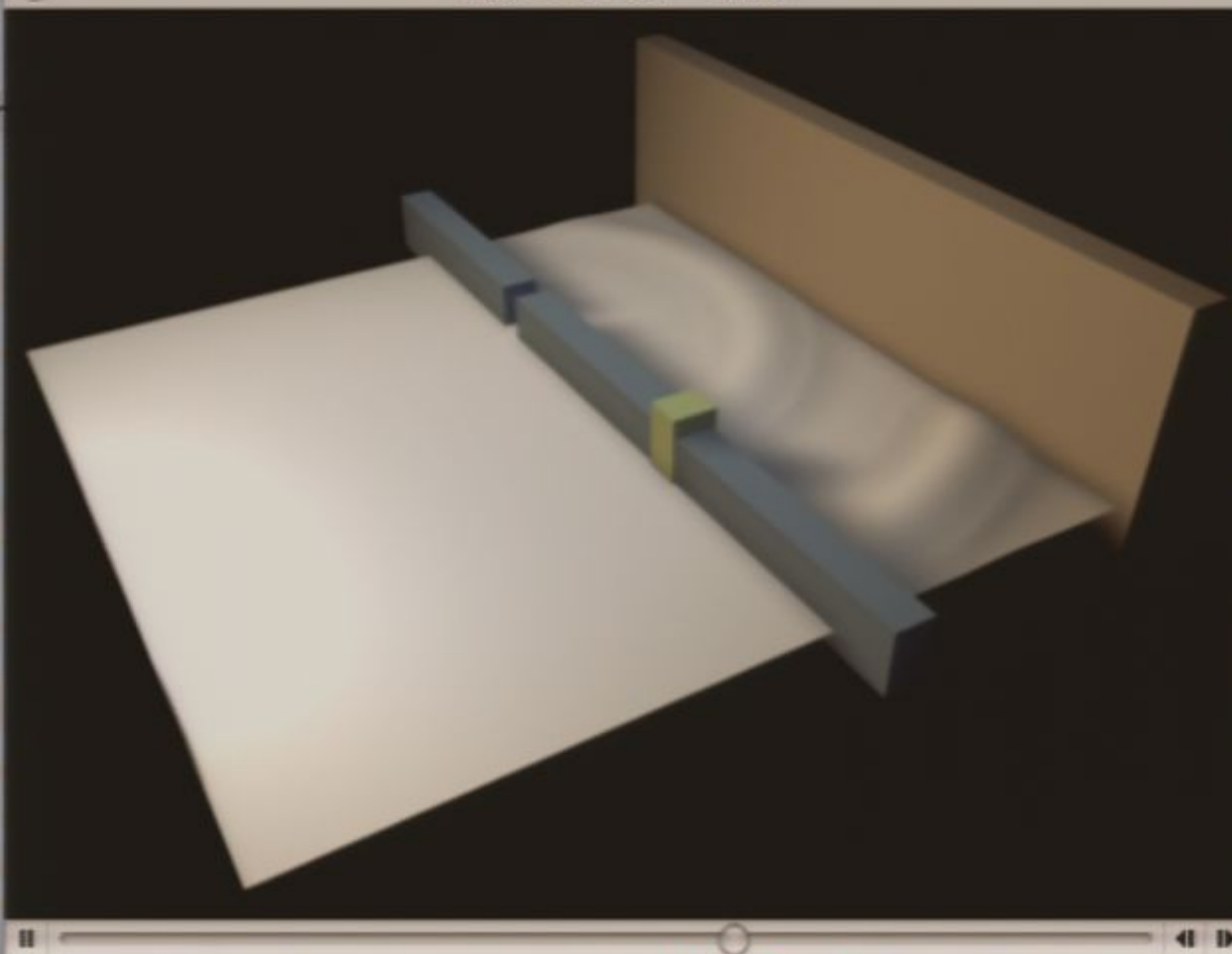


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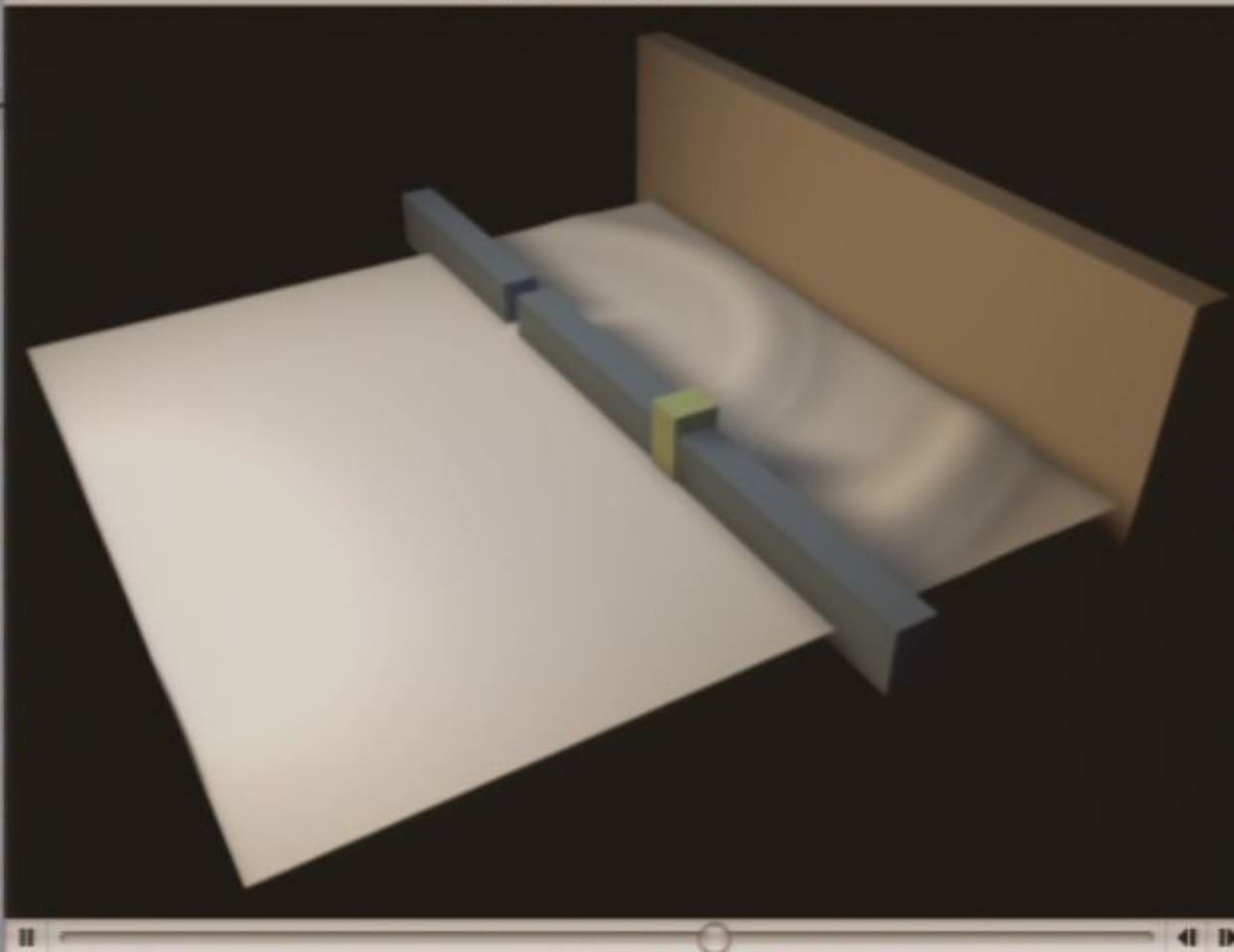


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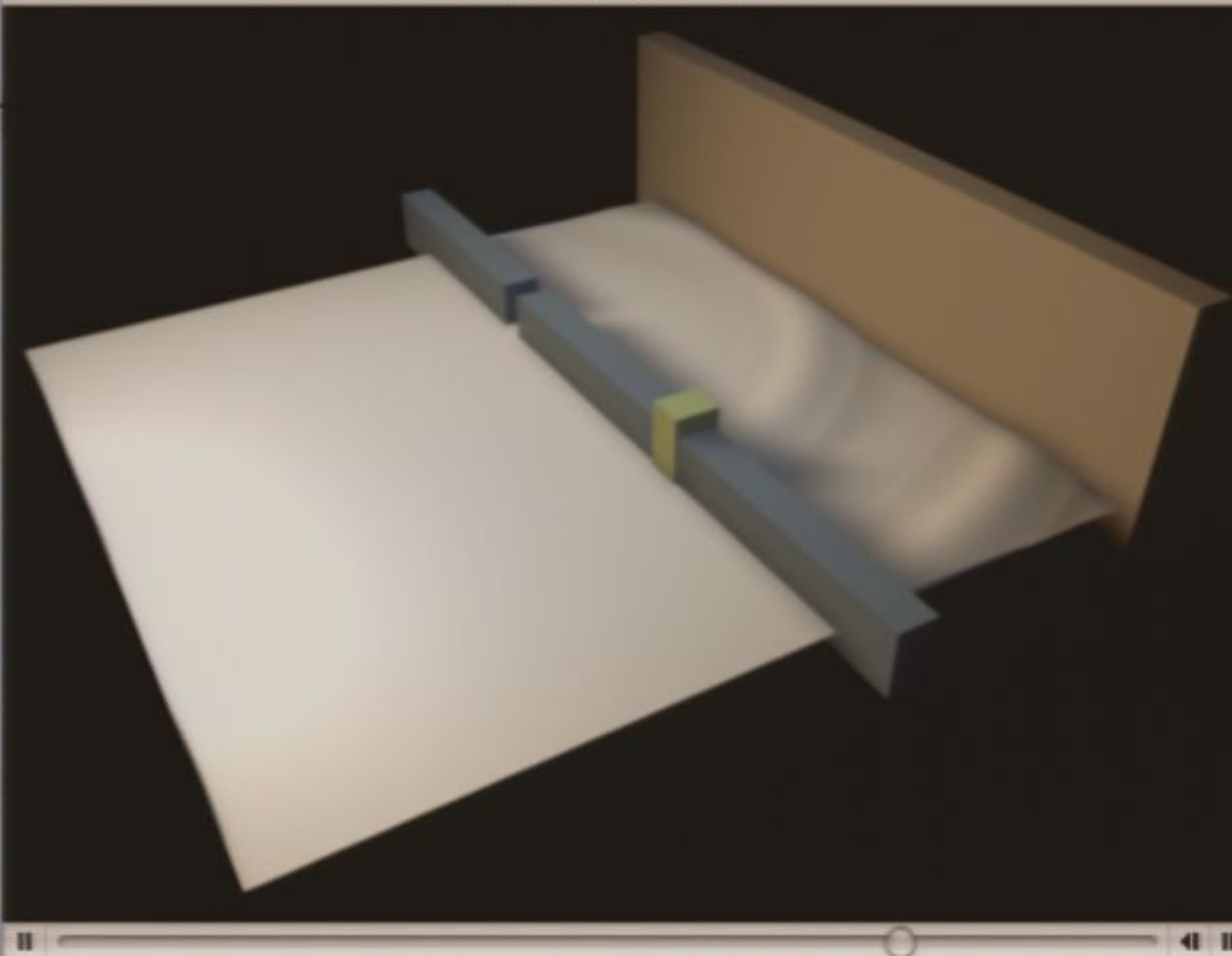


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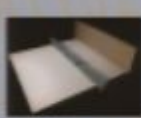
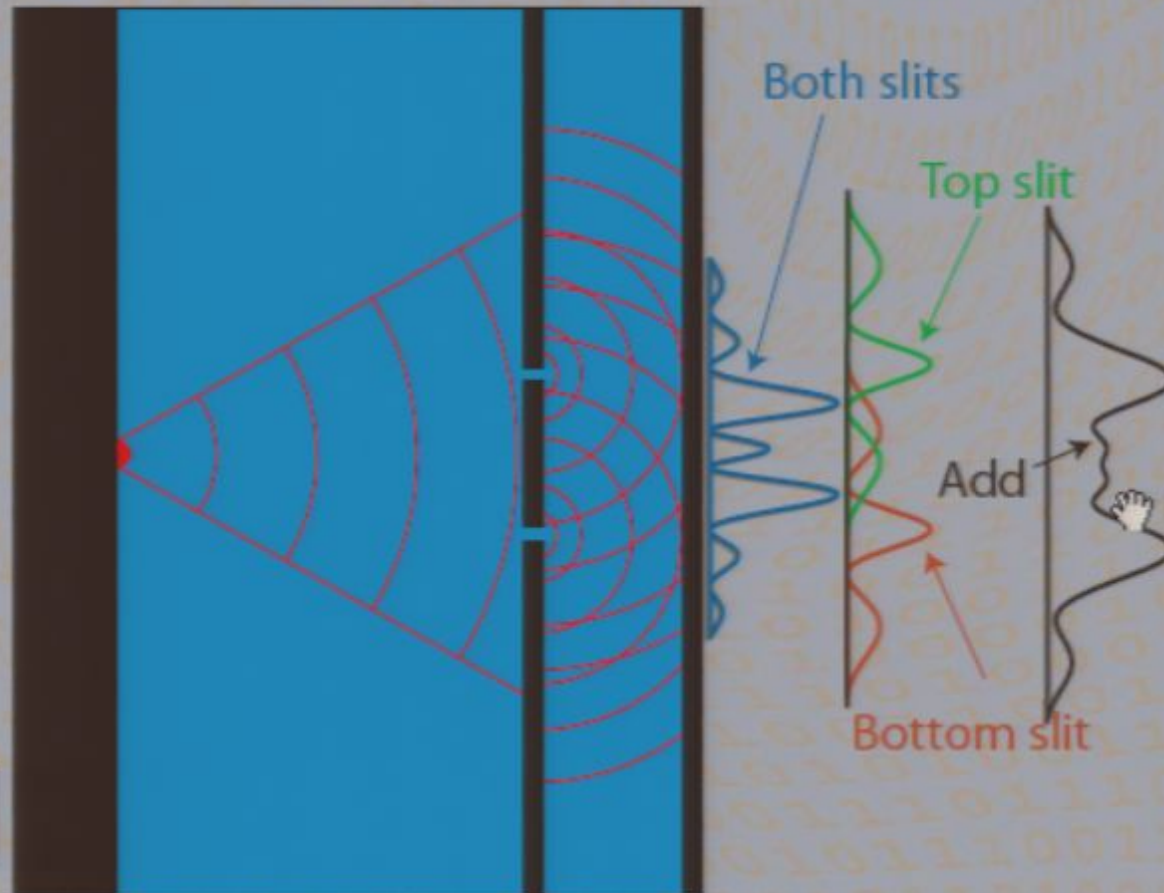
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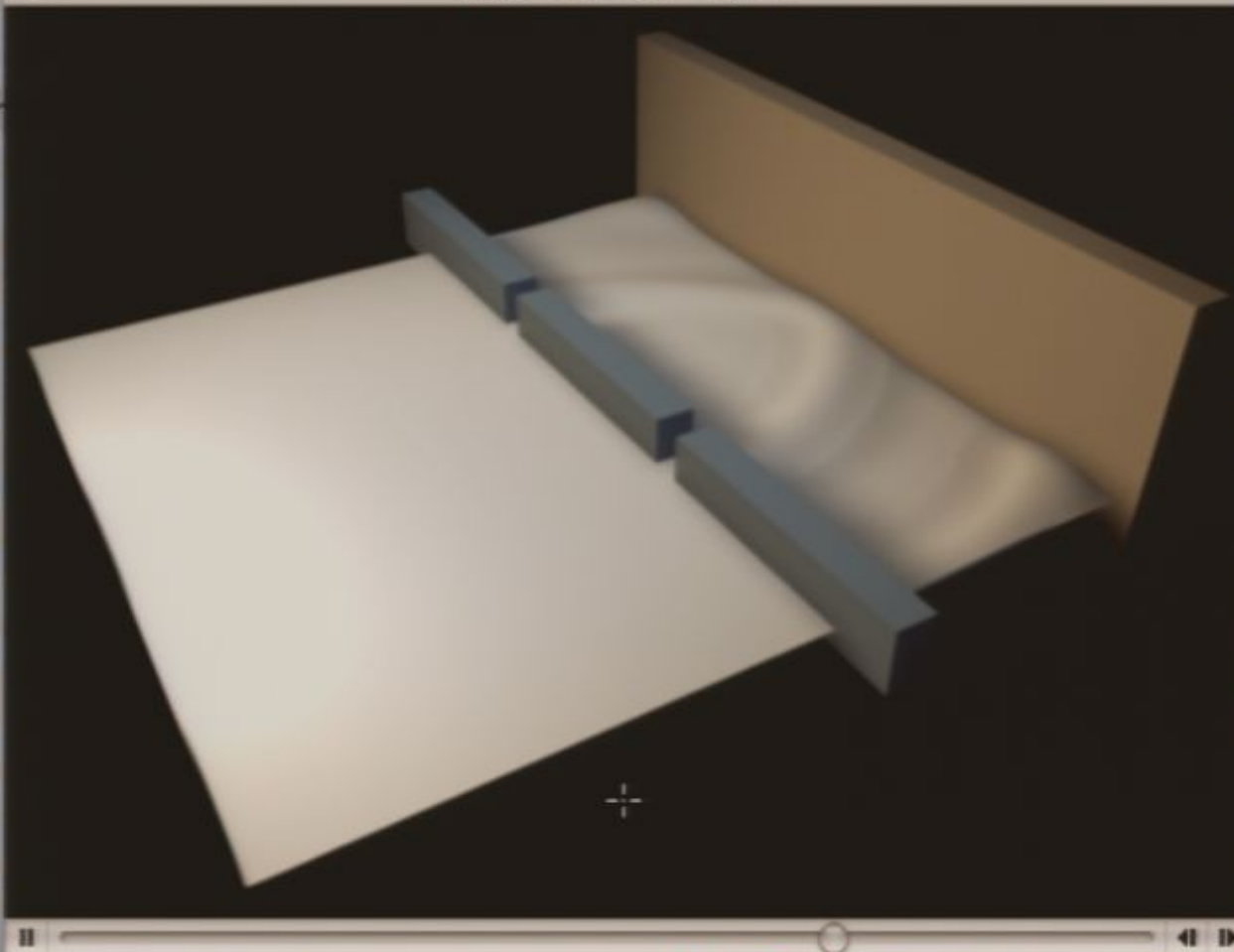


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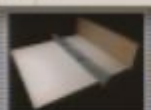
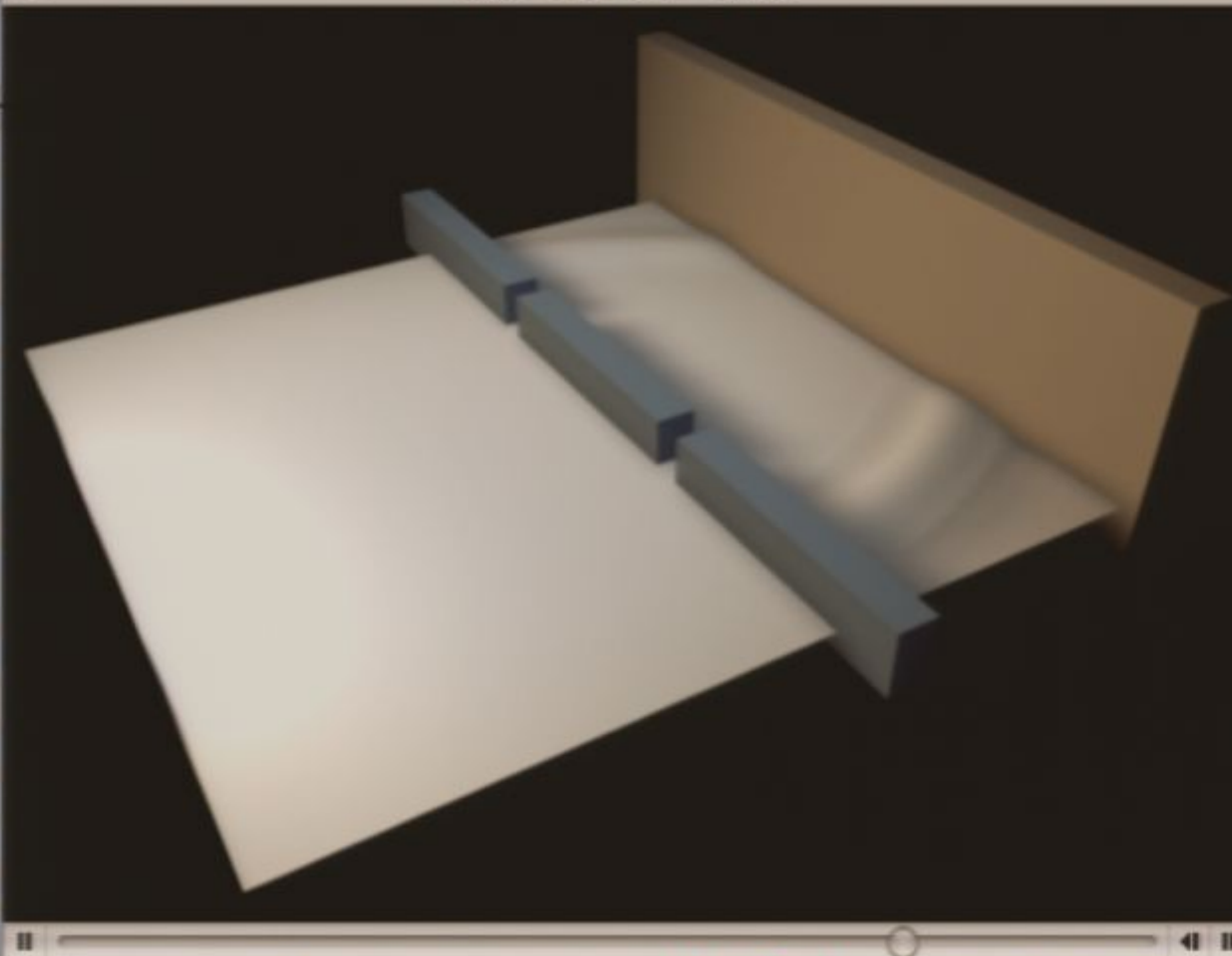


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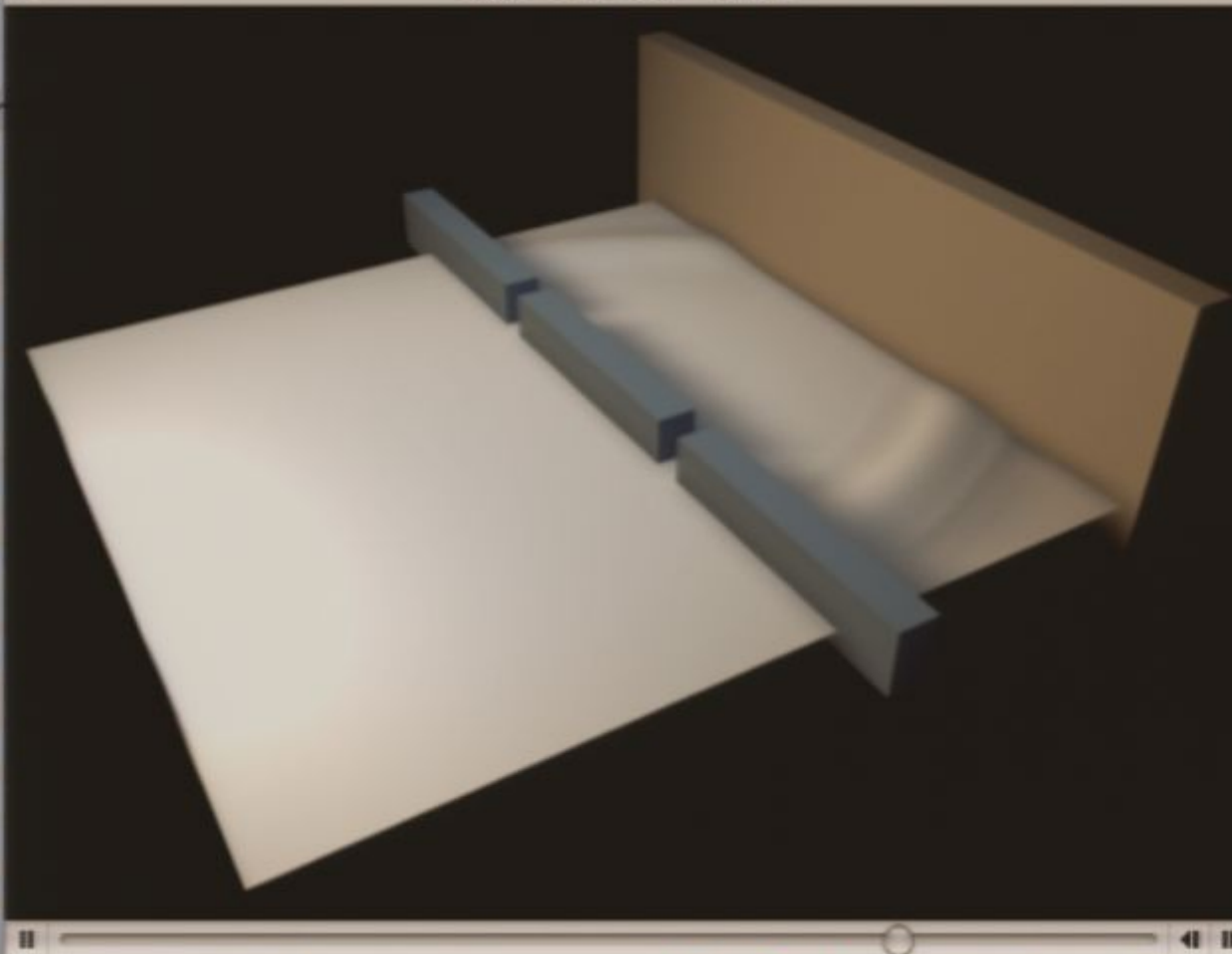


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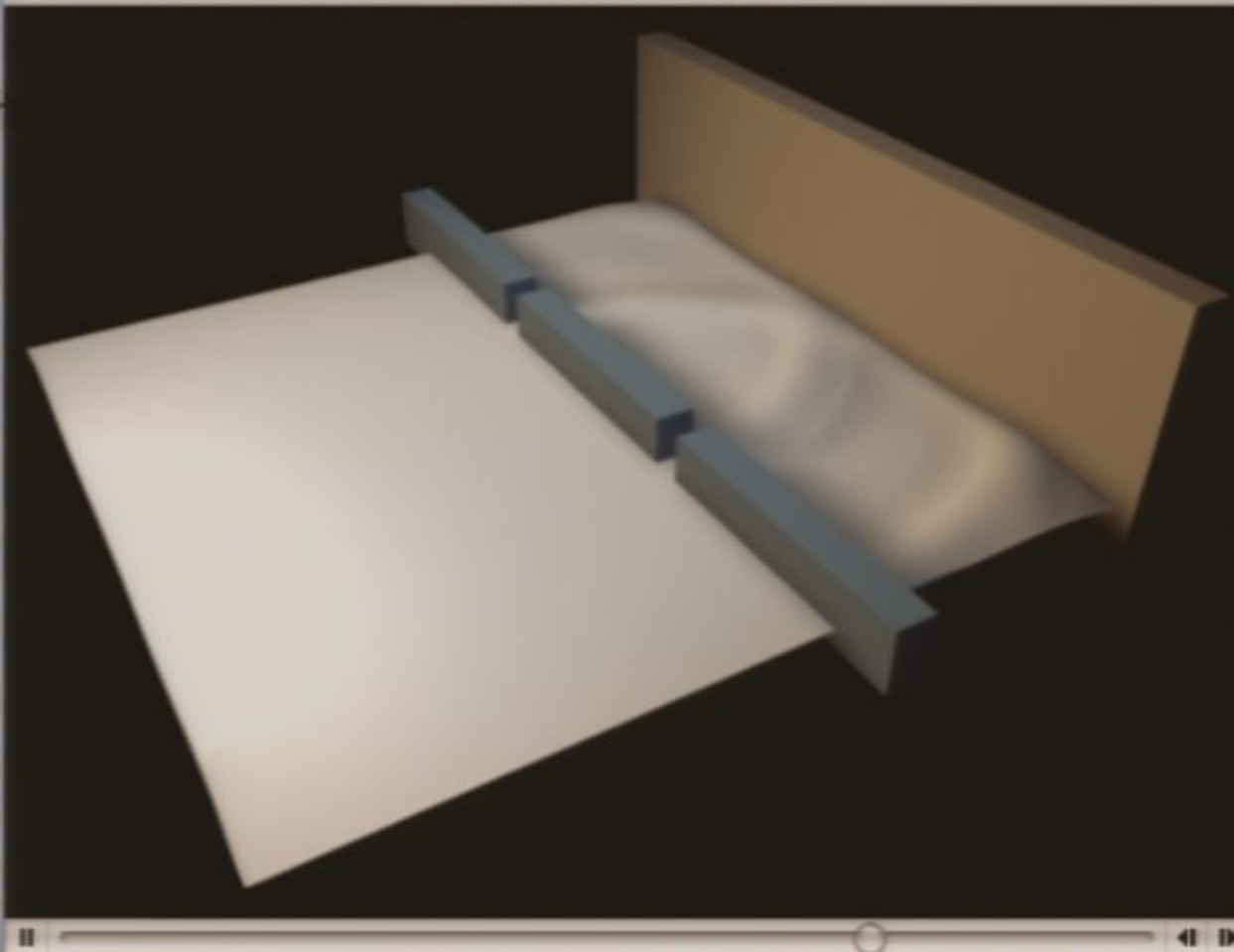


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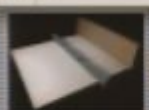
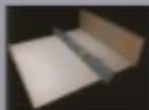
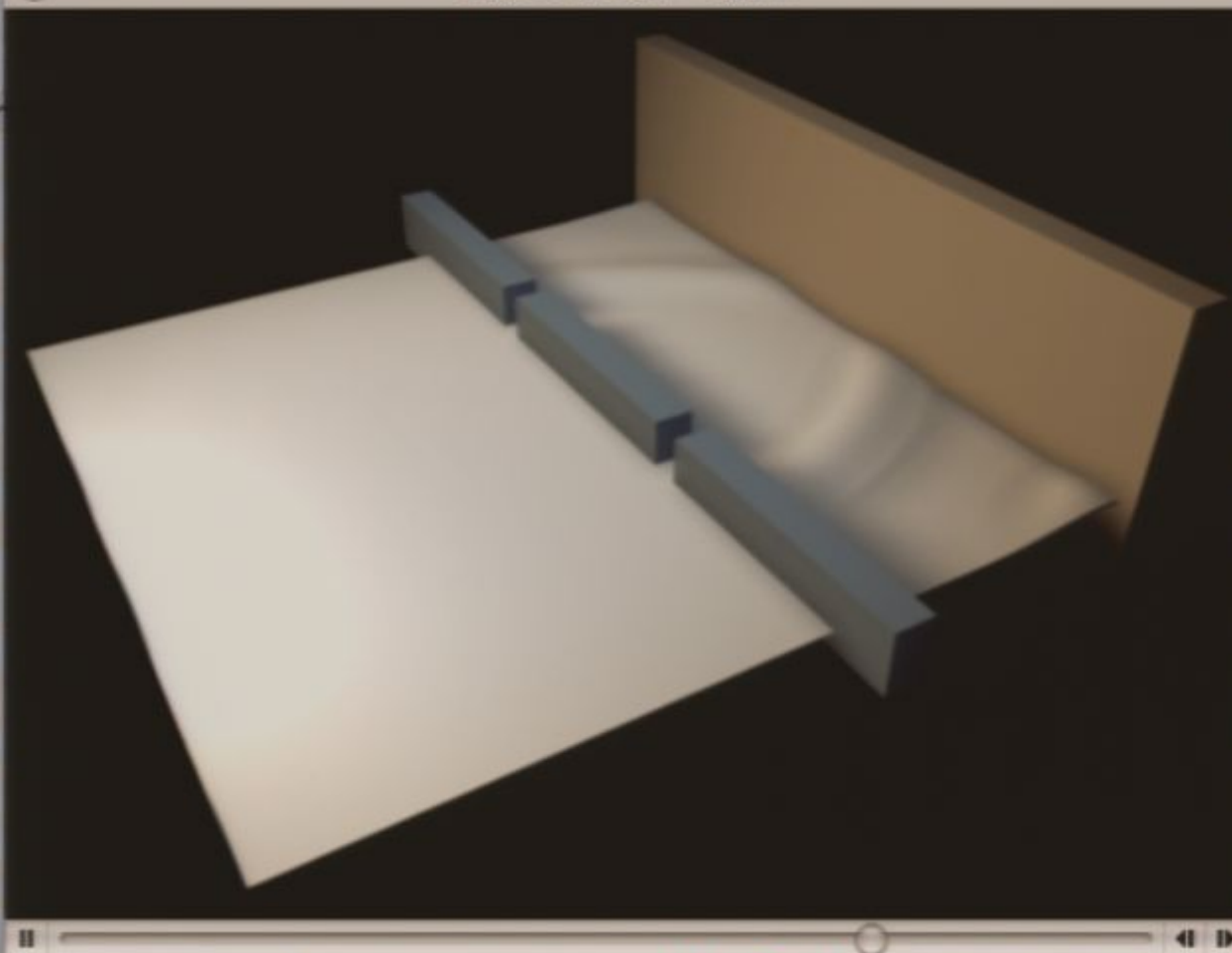


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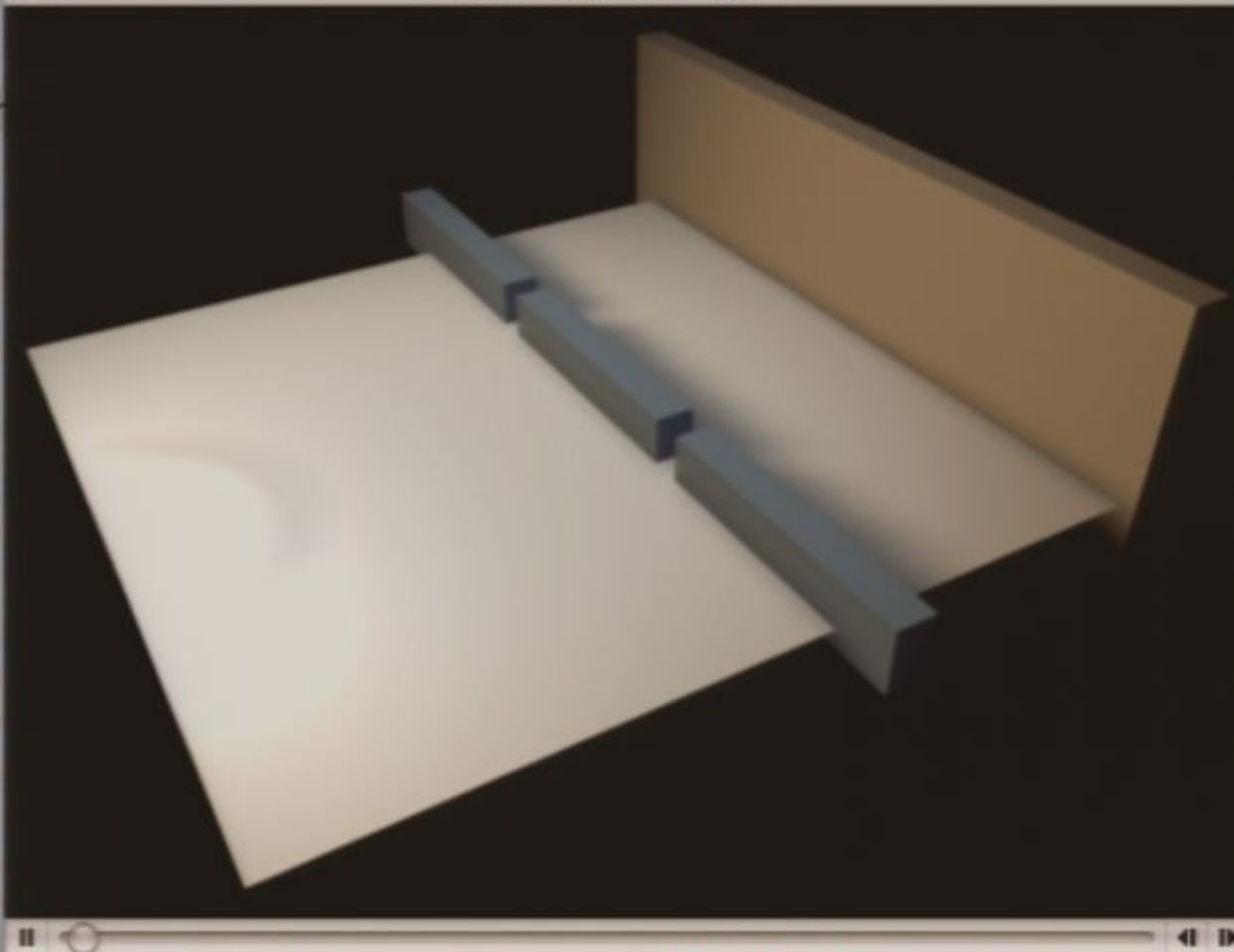


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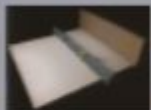
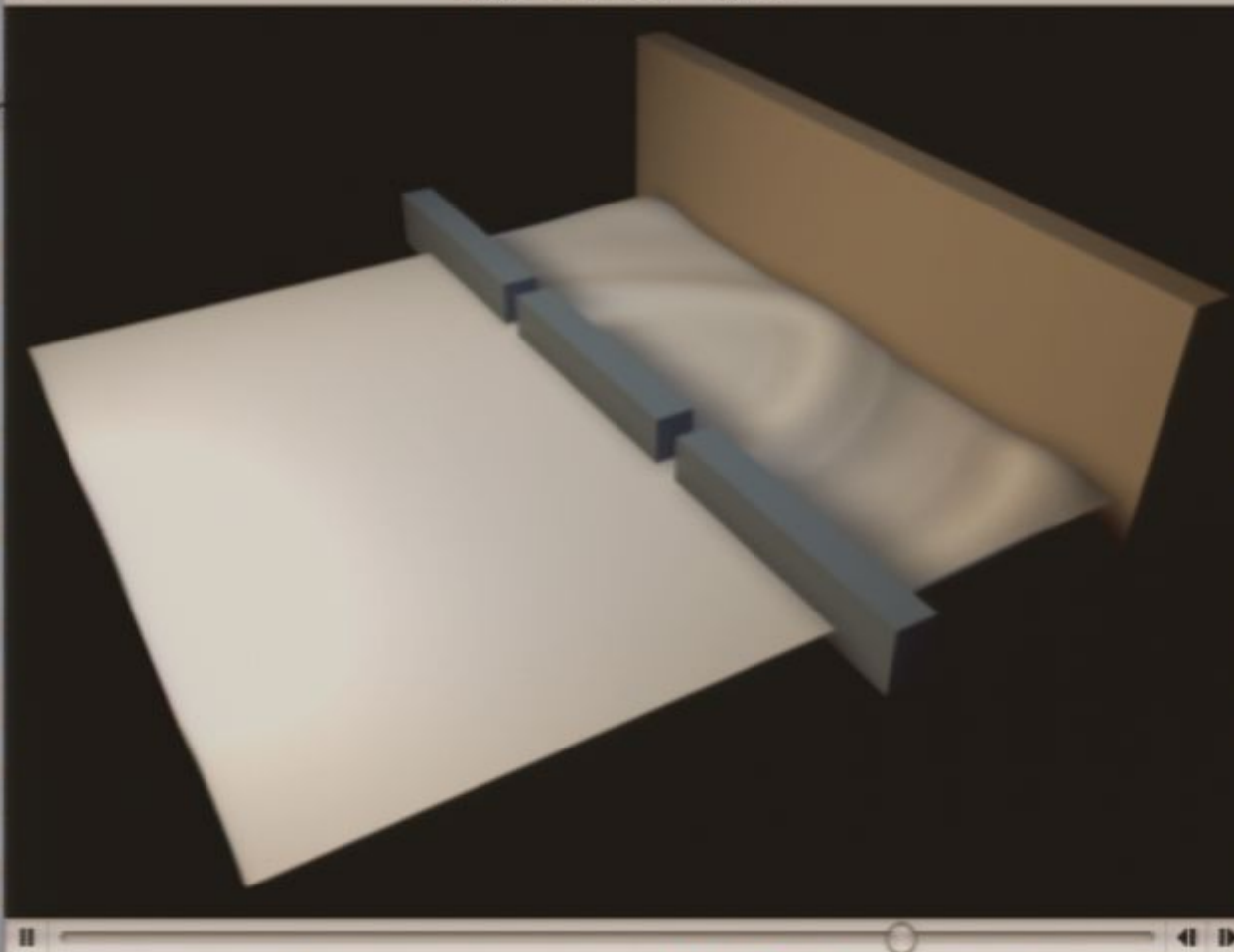


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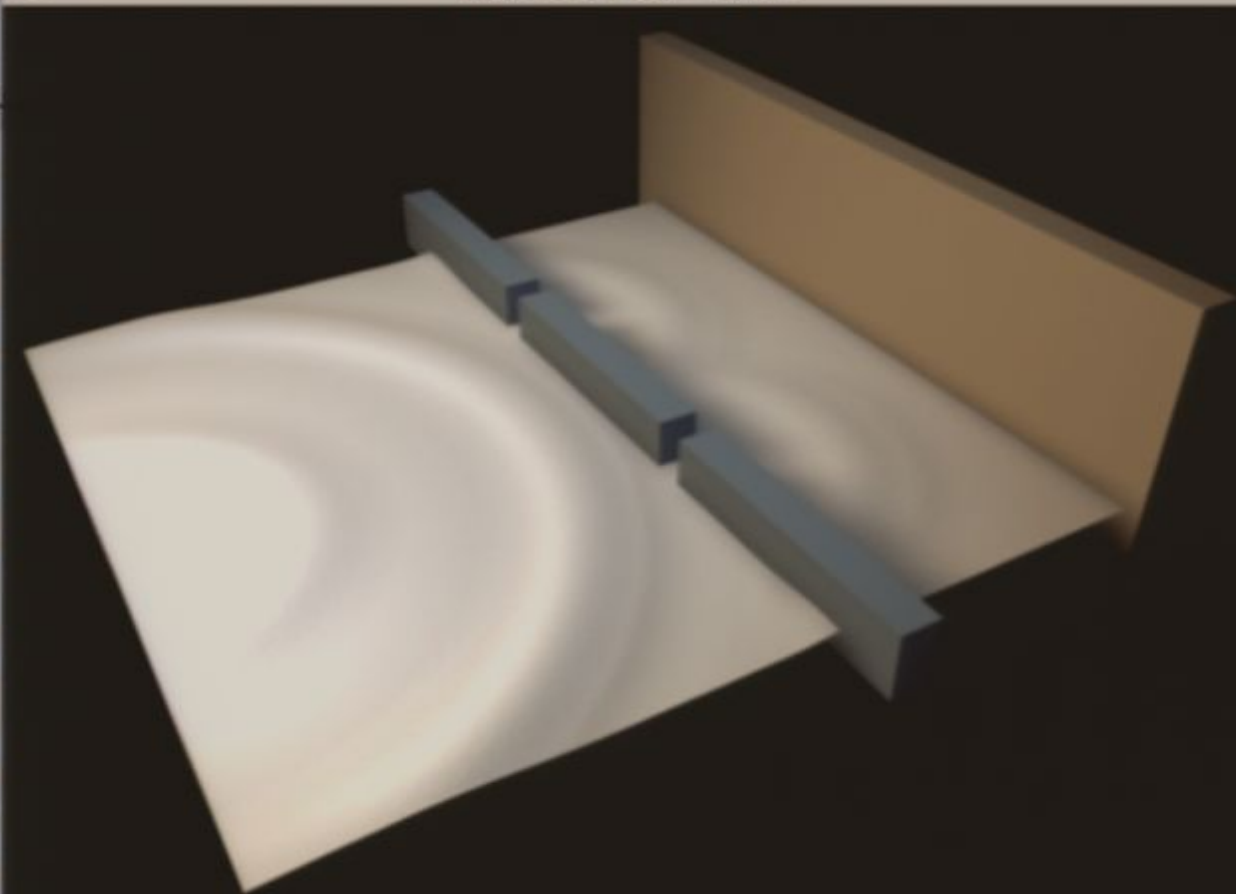


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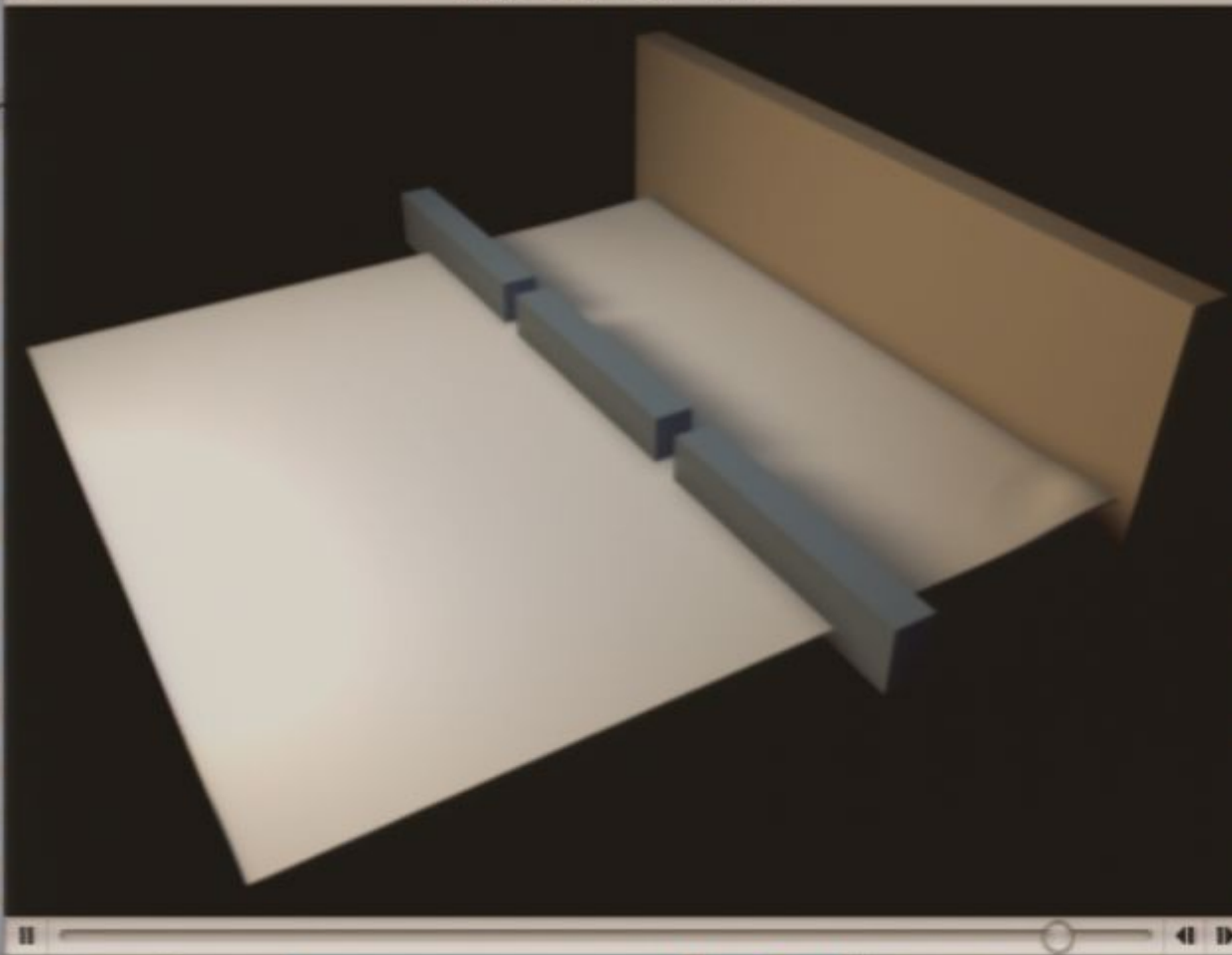


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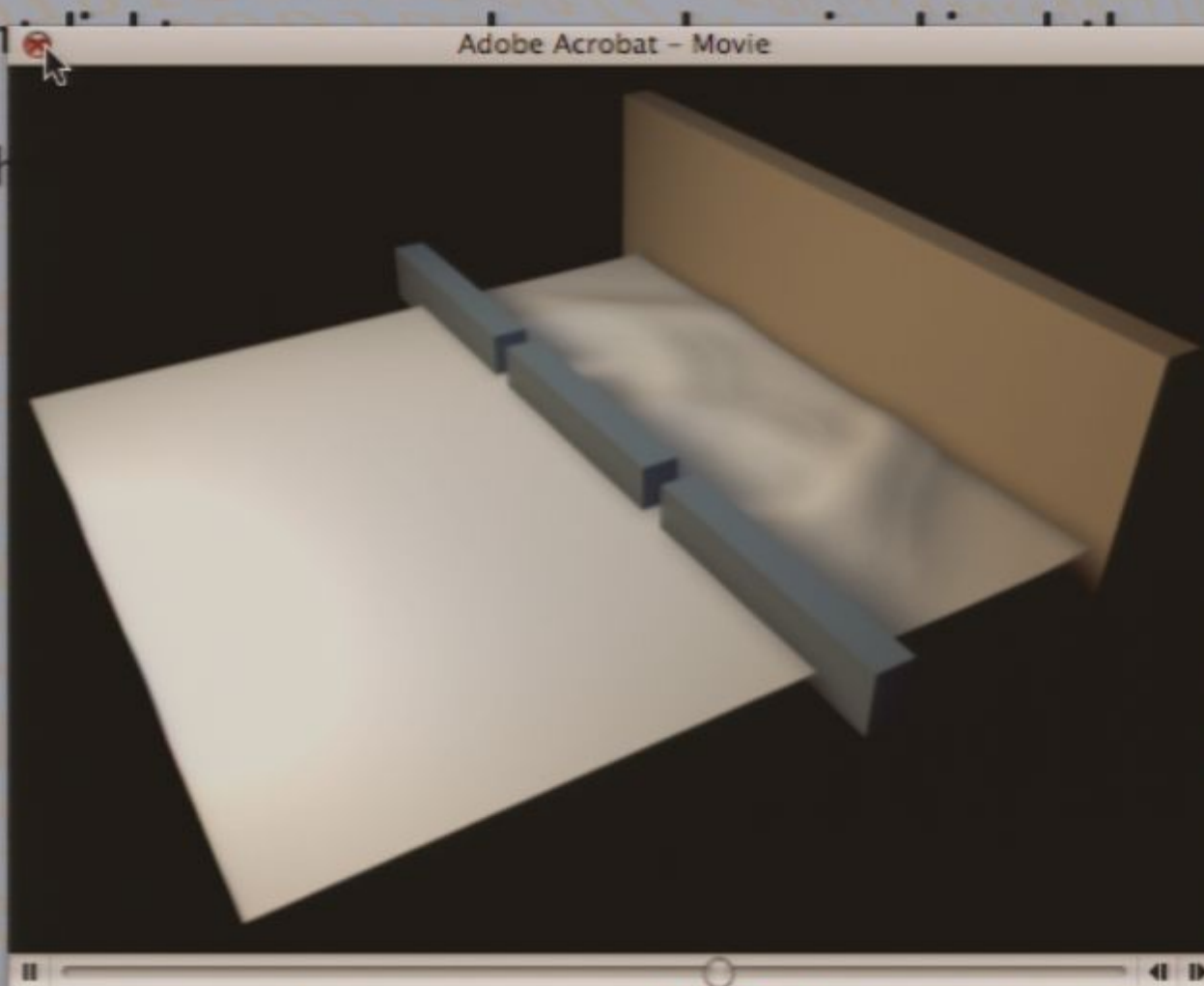
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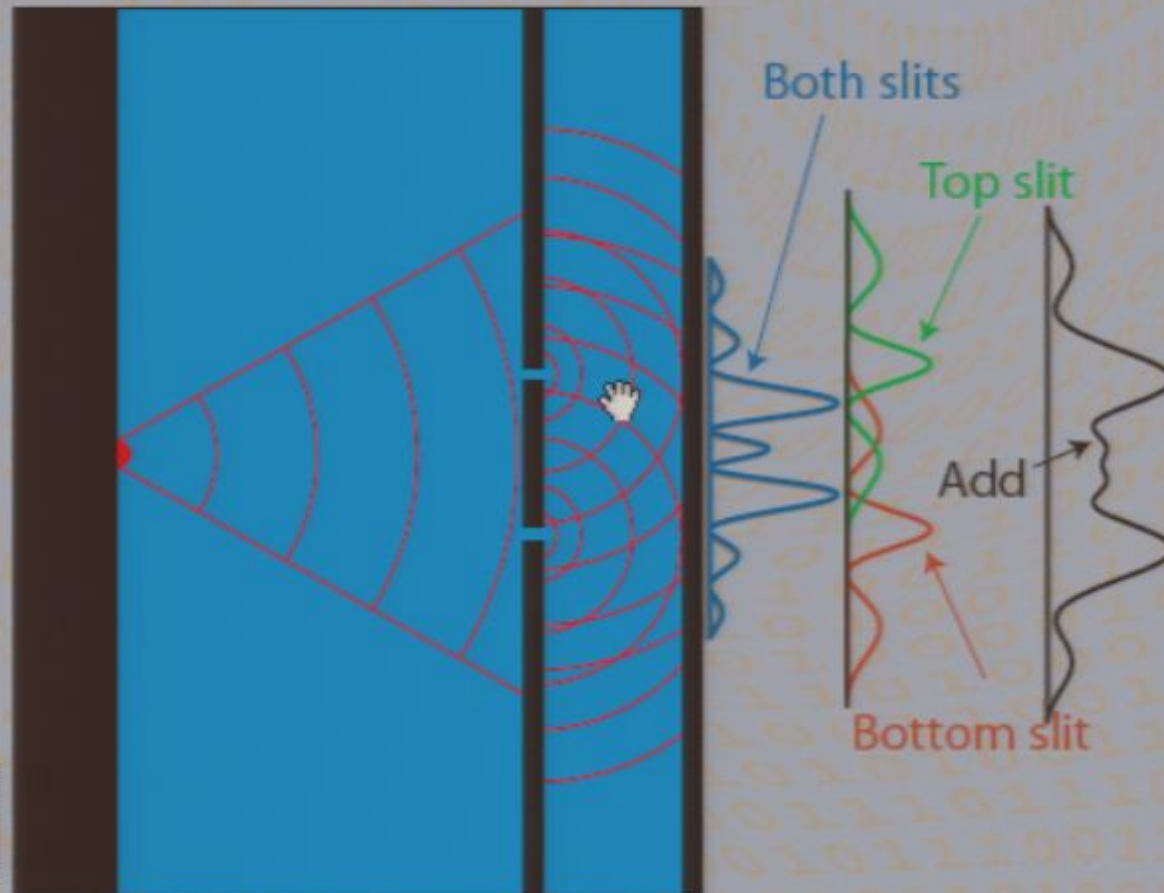
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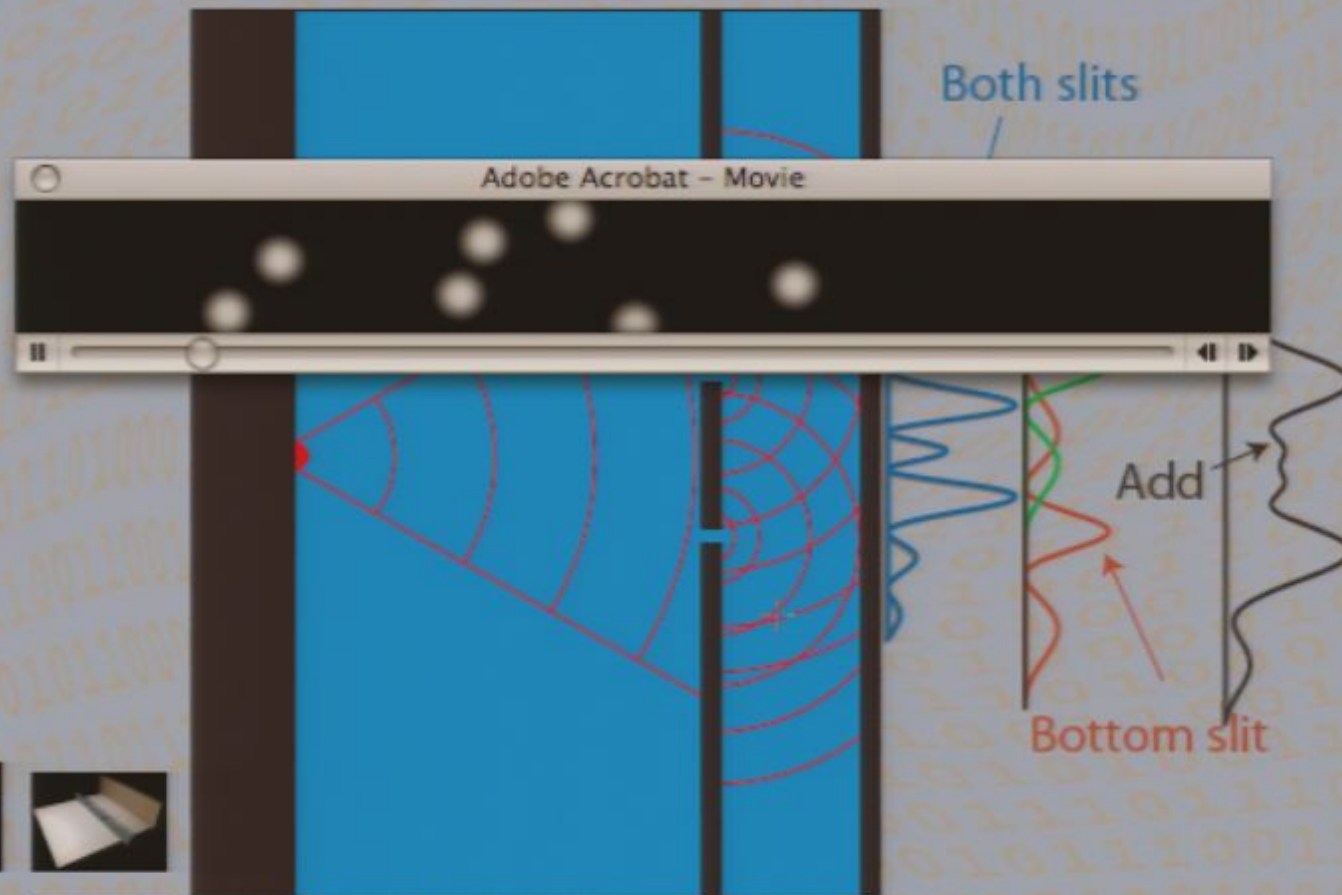
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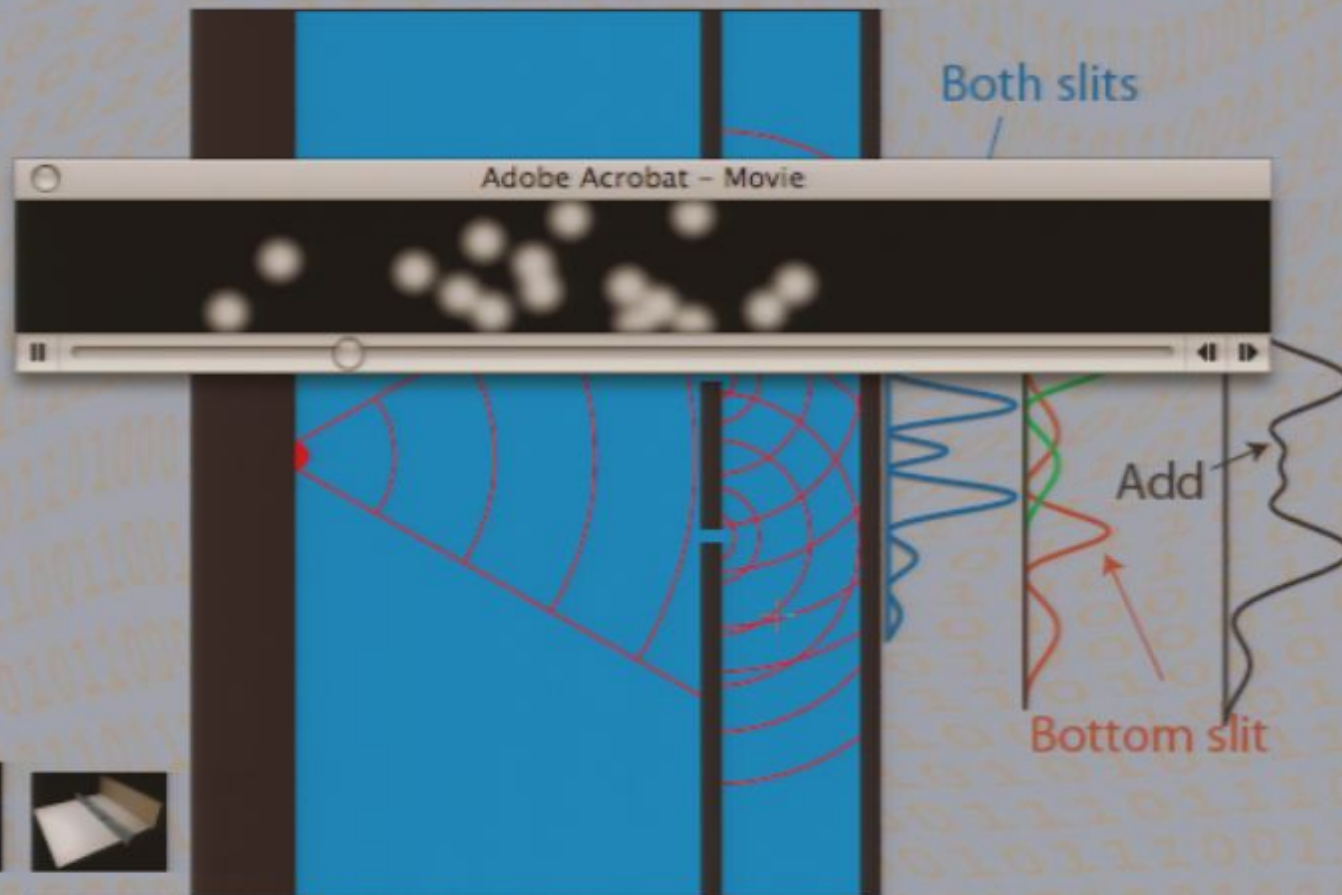
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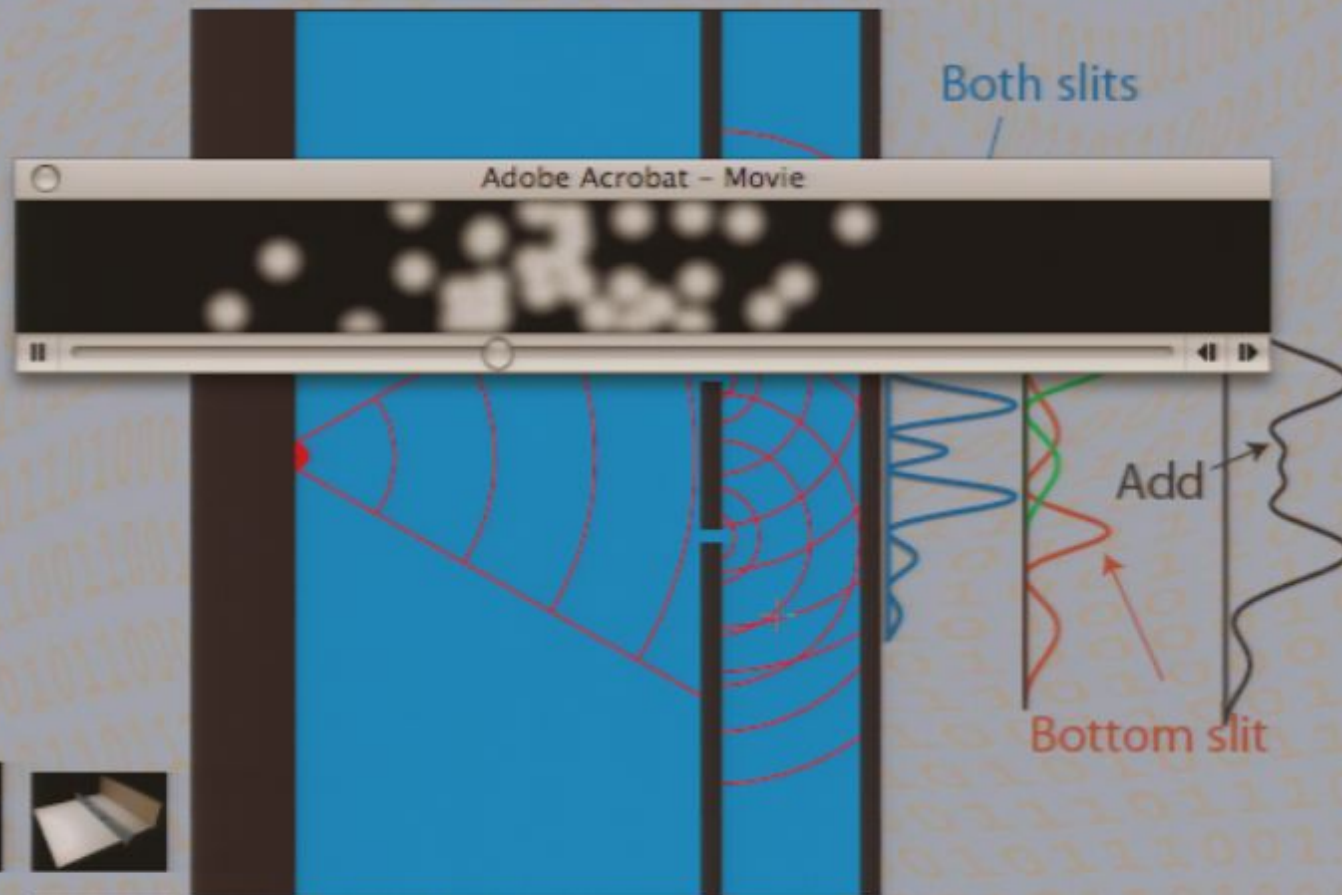
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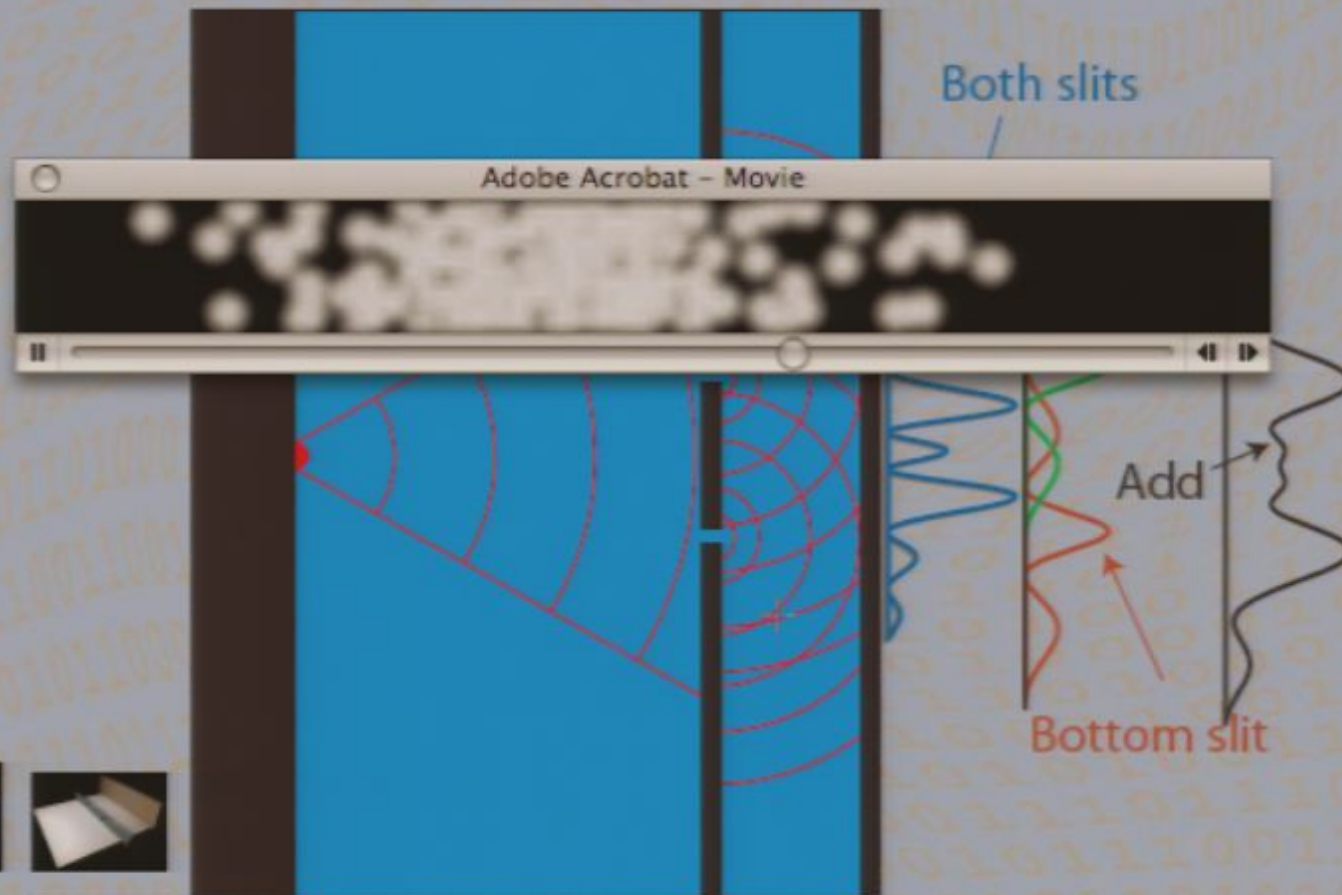
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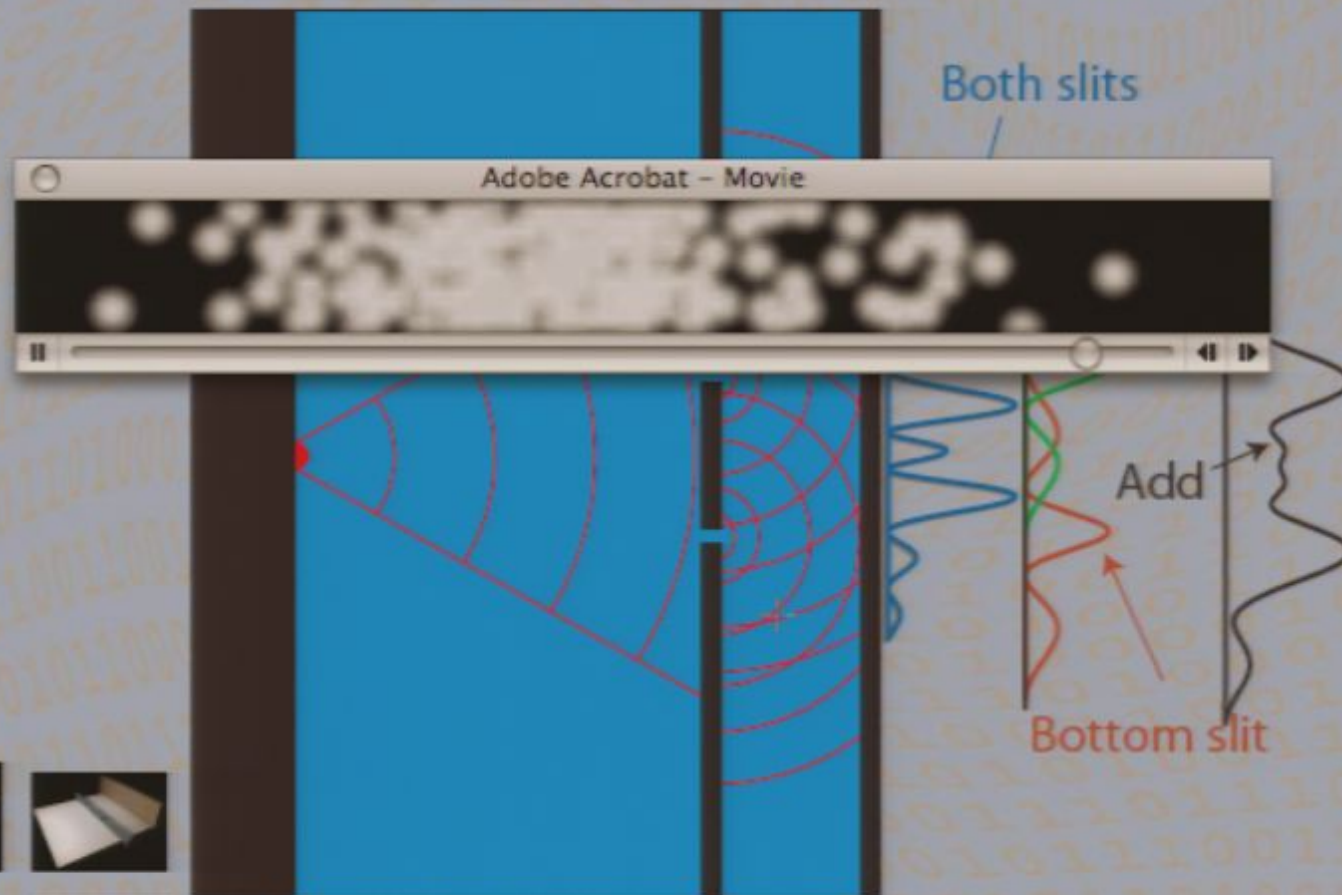
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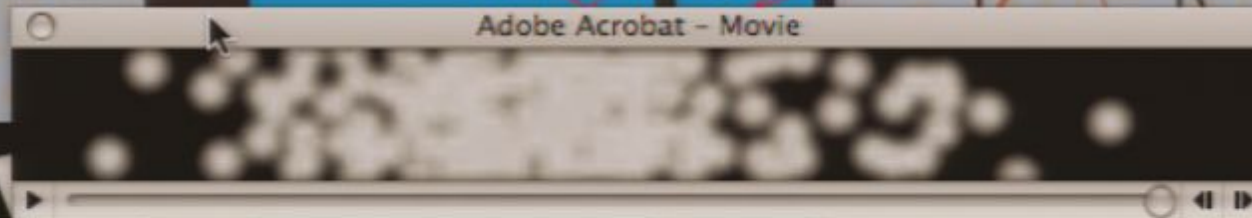
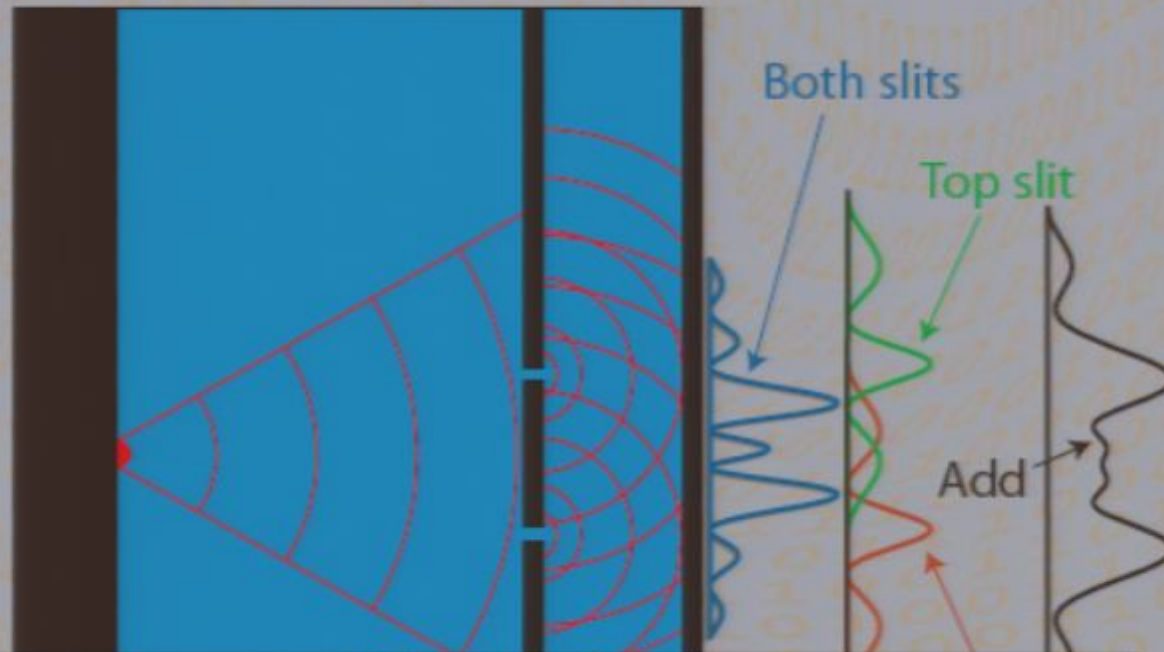
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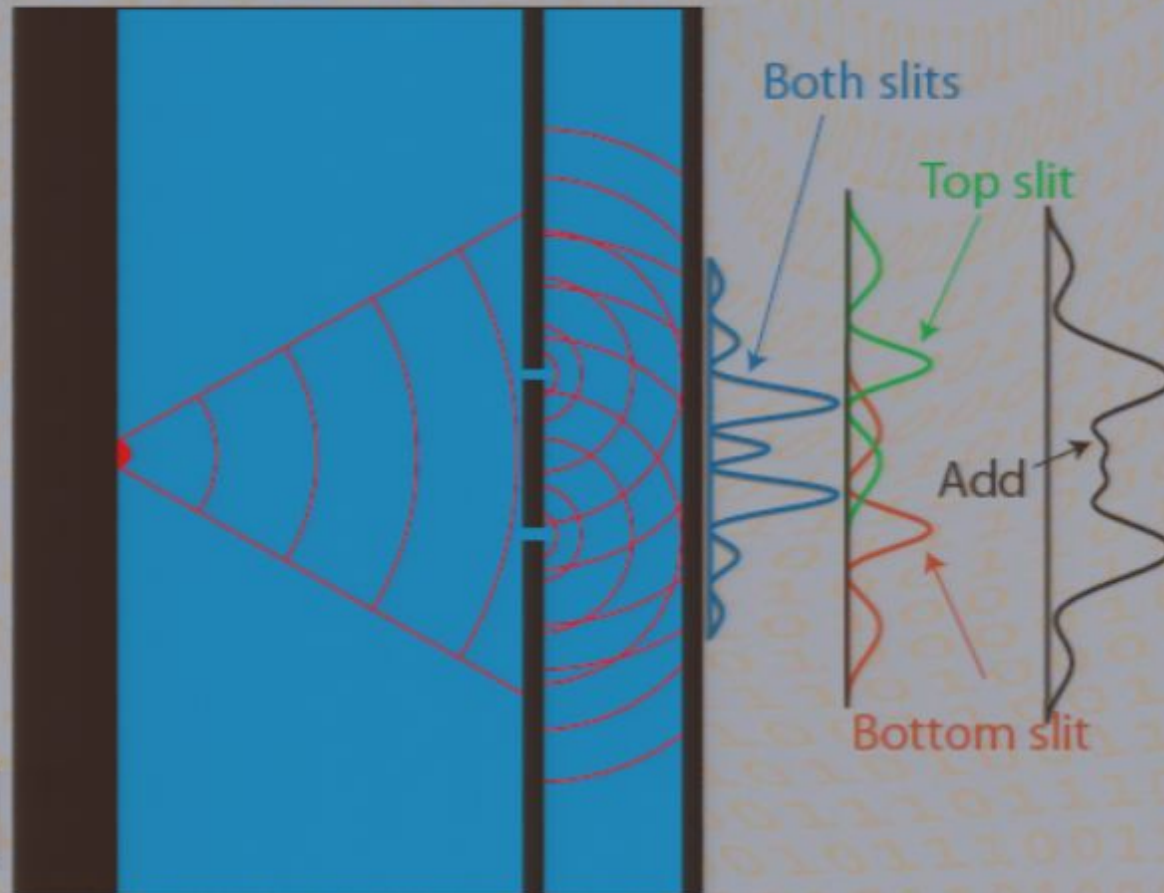
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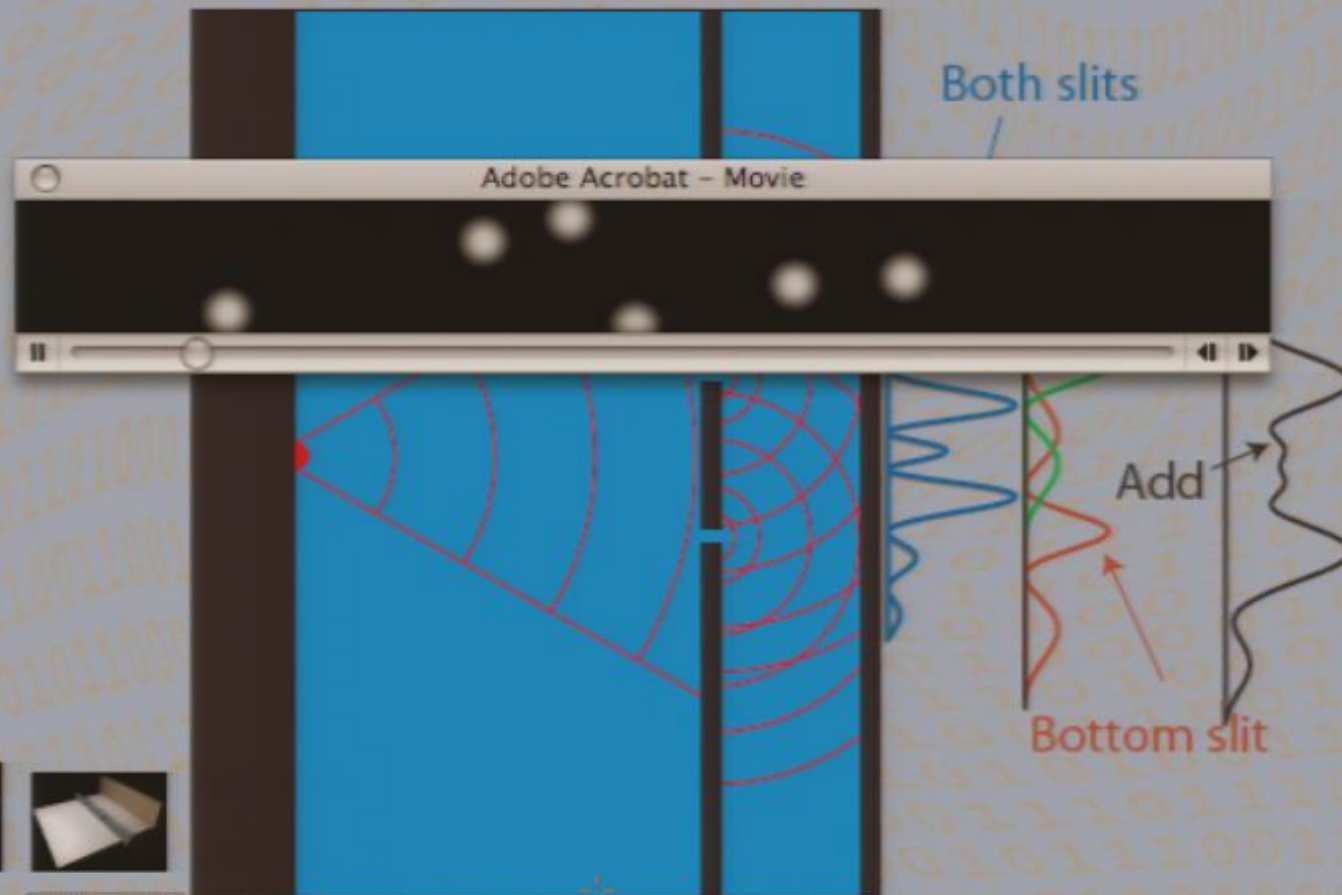
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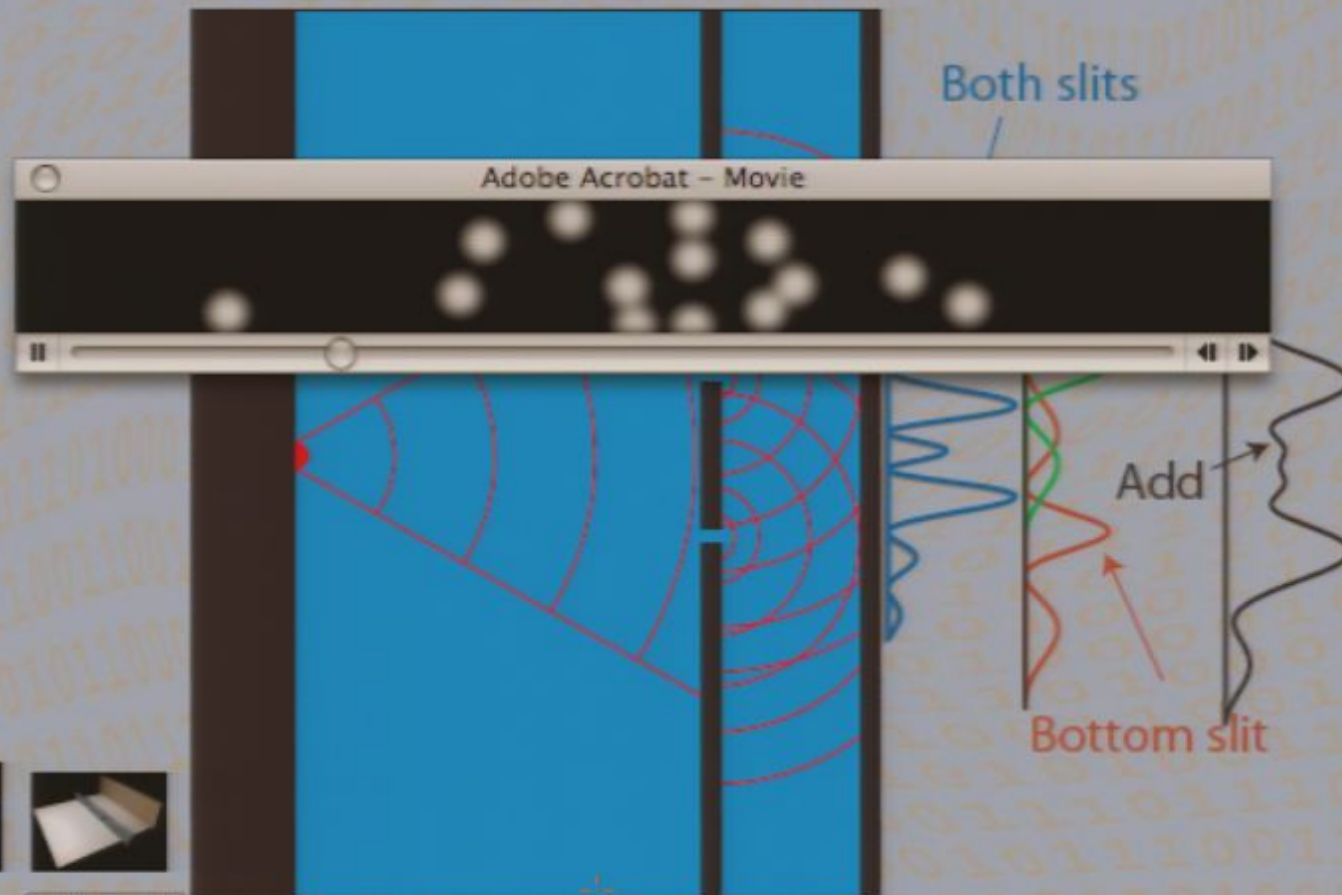
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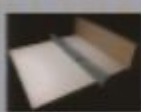
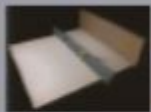
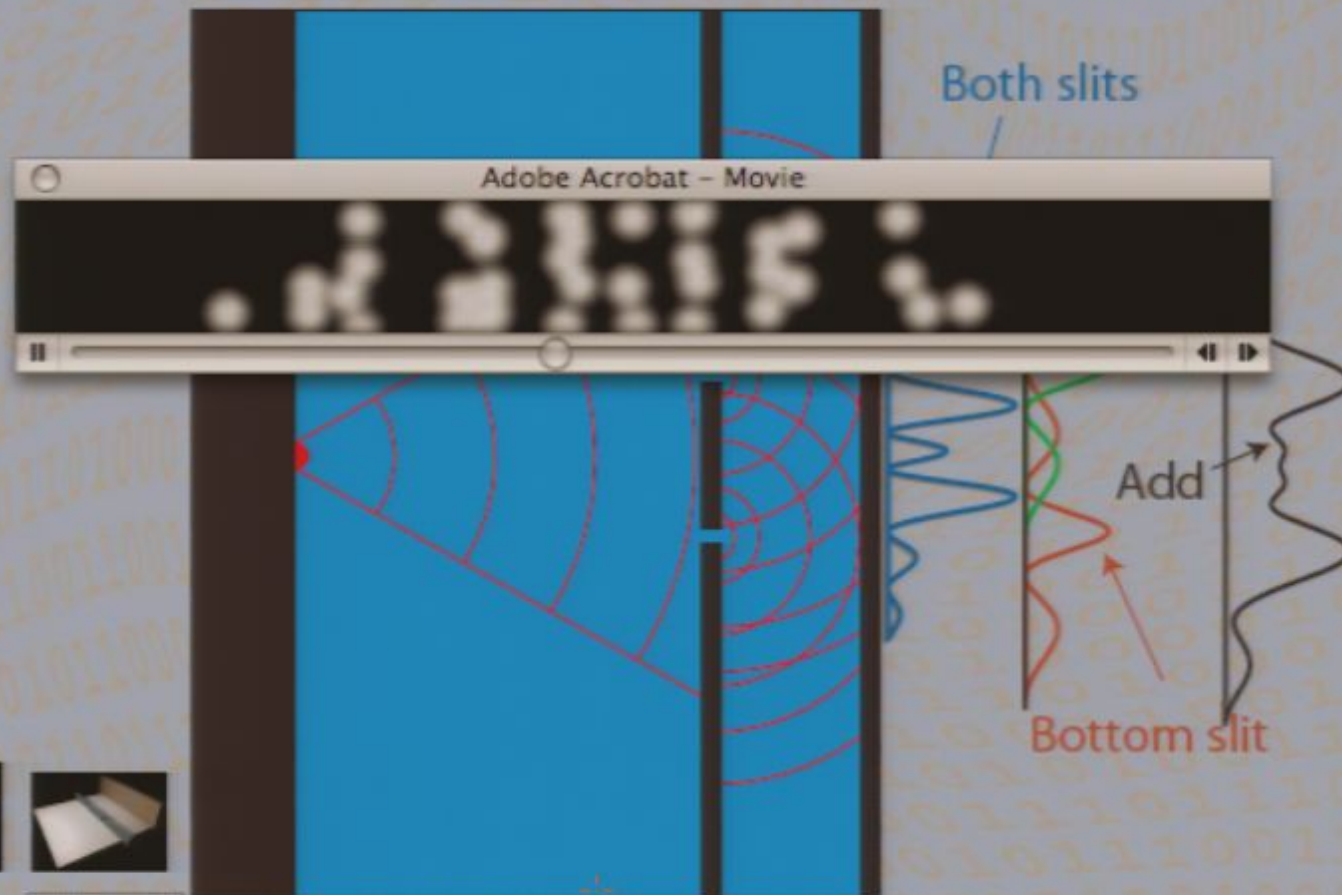
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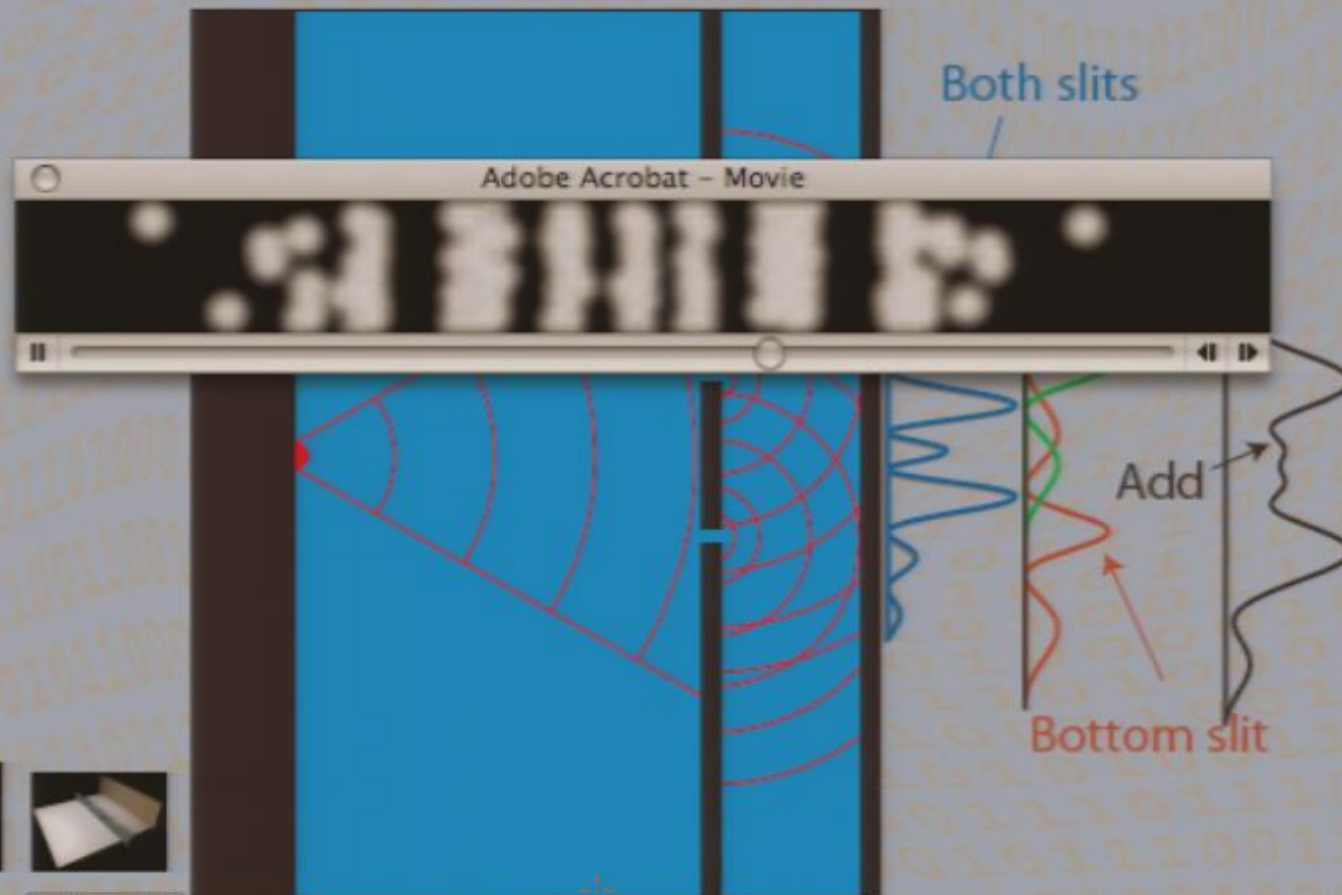
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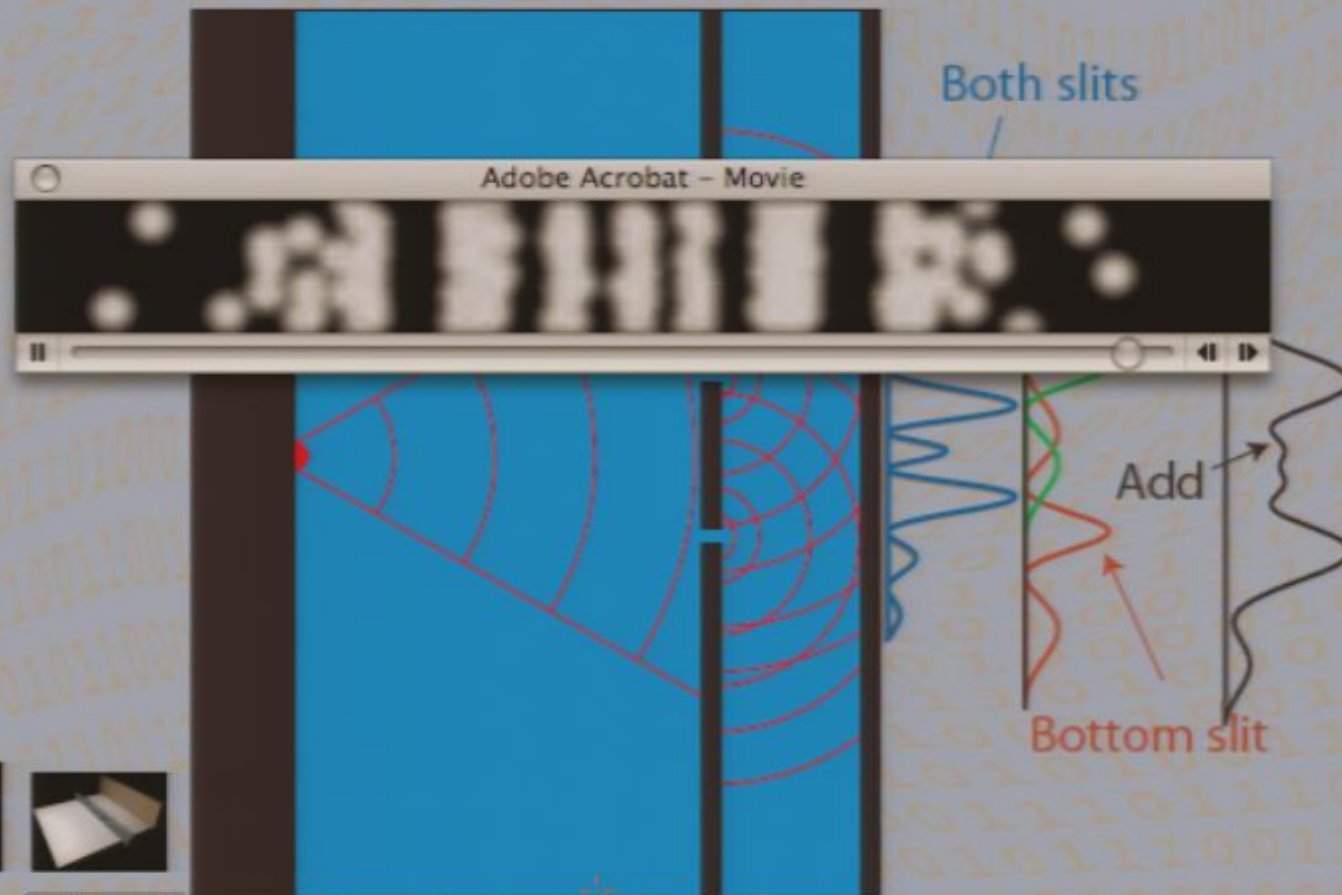
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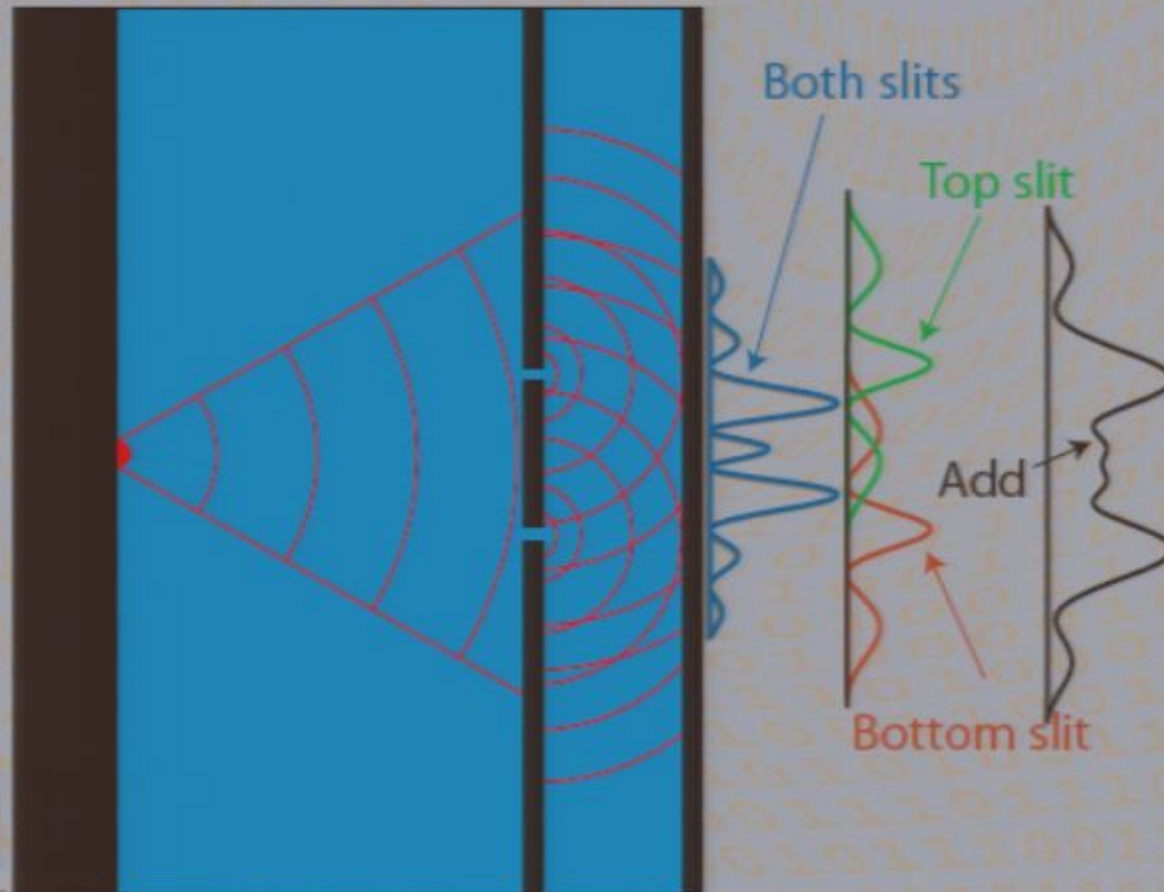
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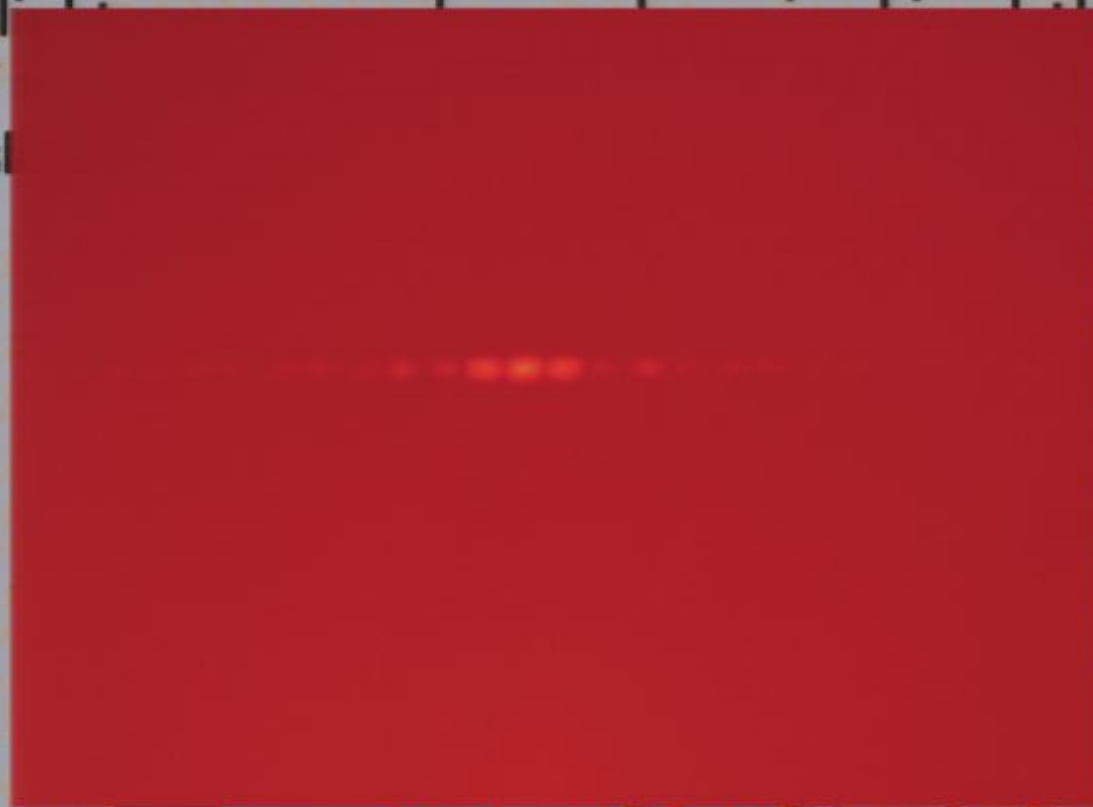
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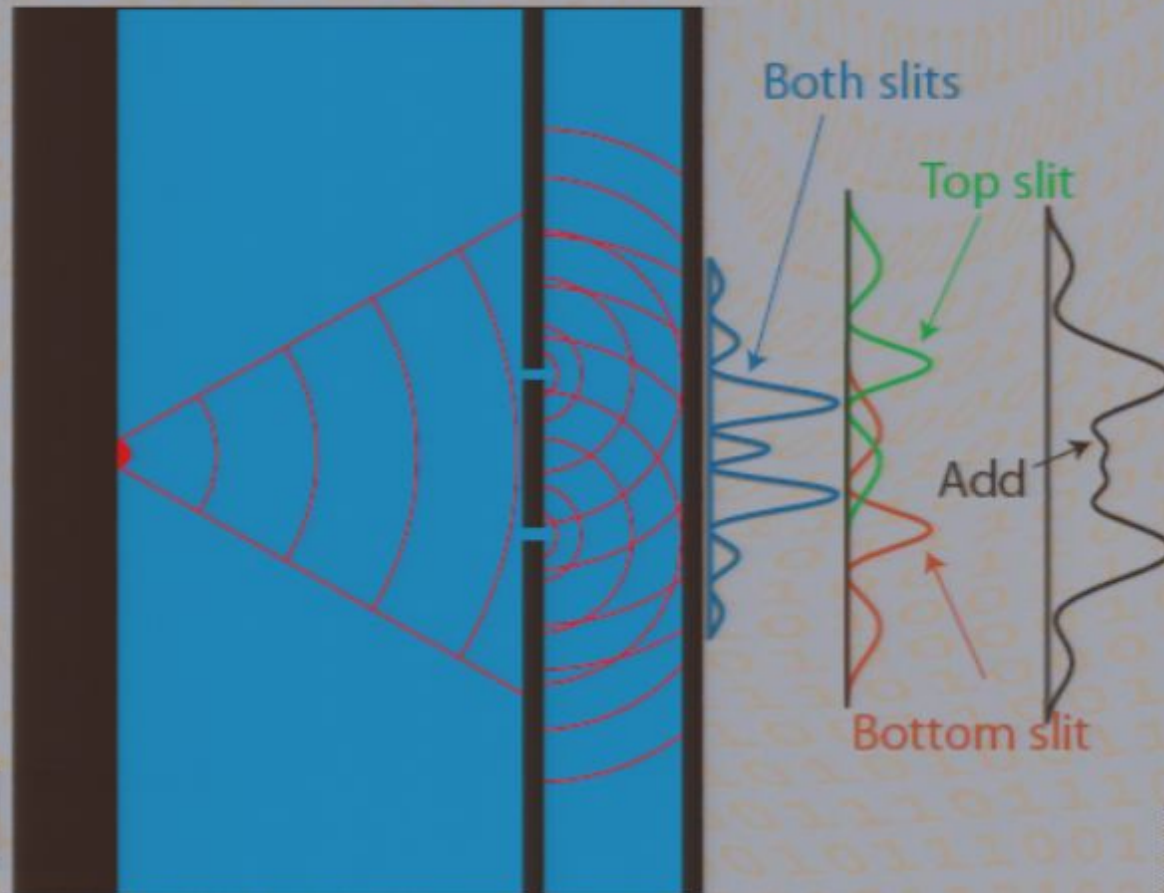
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A coherent light source is directed through 2 slits, the result of the interference pattern is the final result when both slits are open.



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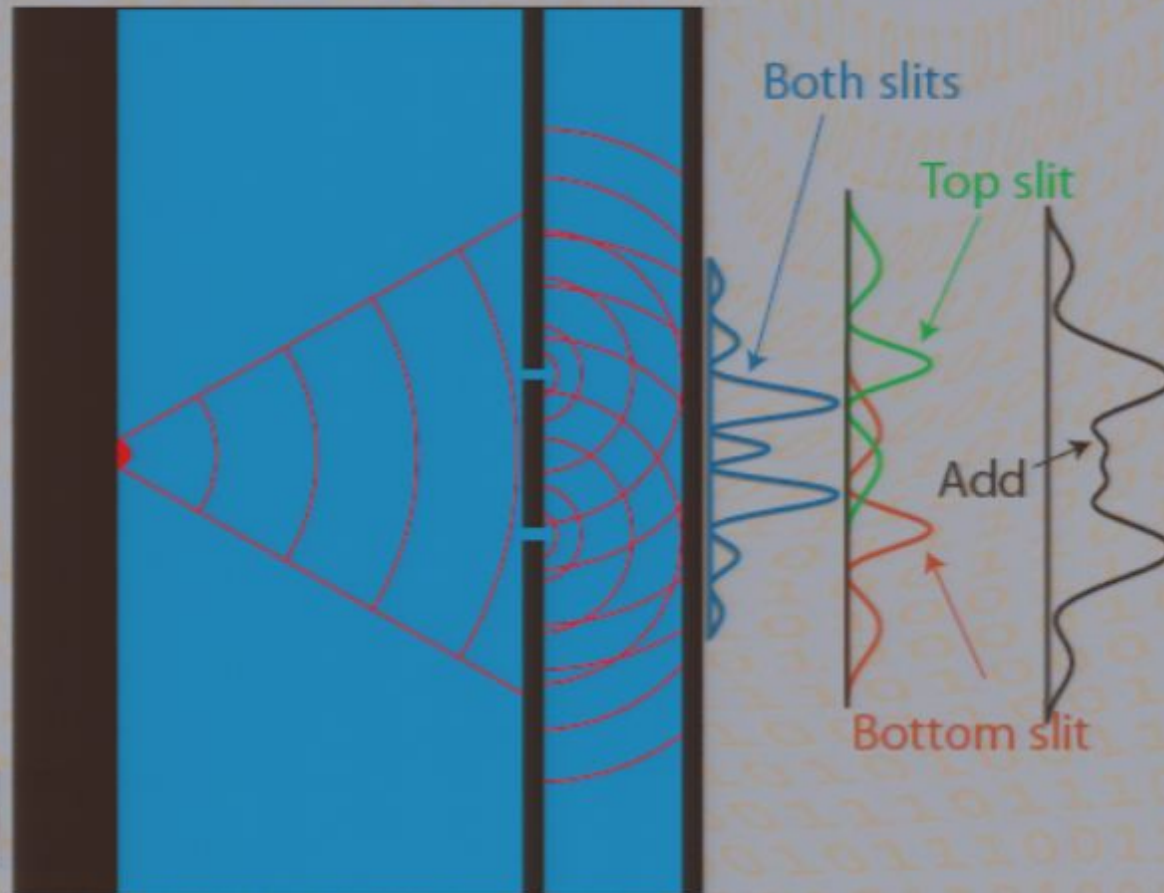


Two properties of Quantum Mechanics:

- Quantum systems behave both as waves and particles. These particles can be at more than one place at once.
- Looking at quantum systems always leaves a fingerprint.

Basics of Quantum Mechanics

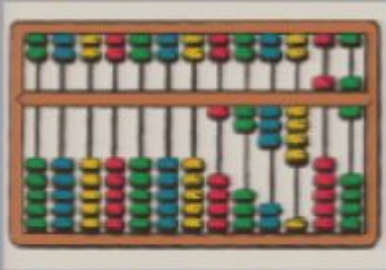
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Early computing devices



Abacus



Babbage
Analytical engine



MIT's mechanical mind

Mathematical Problems

Lecture delivered before the International Congress of Mathematicians at Paris in 1900

By Professor David Hilbert

2. The compatibility of the arithmetical axioms

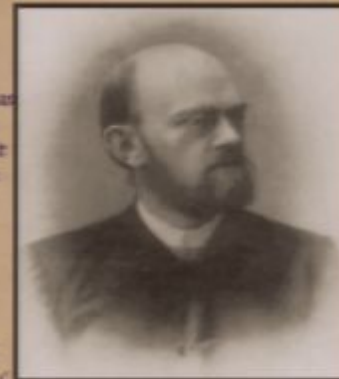
When we are engaged in investigating the foundations of a science, we must set up a system of axioms which contains an exact and complete description of the relations subsisting between the elementary ideas of that science. The axioms so set up are at the same time the definitions of those elementary ideas; and no statement within the realm of the science whose foundation we are testing is held to be correct unless it can be derived from those axioms by means of a finite number of logical steps. Upon closer consideration the question arises: Whether, in any way, certain statements of single axioms depend upon one another, and whether the axioms may not therefore contain certain parts in common, which must be isolated if one wishes to arrive at a system of axioms that shall be altogether independent of one another.

But above all I wish to designate the following as the most important among the numerous questions which can be asked with regard to the axioms: To prove that they are not contradictory, that is, that a definite number of logical steps based upon them can never lead to contradictory results.

In geometry, the proof of the compatibility of the axioms can be effected by constructing a suitable field of numbers, such that analogous relations between the numbers of this field correspond to the geometrical axioms. Any contradiction in the deductions from the geometrical axioms must then upon be recognizable in the arithmetic of this field of numbers. In this way the desired proof for the compatibility of the geometrical axioms is made to depend upon the theorem of the compatibility of the arithmetical axioms.

On the other hand a direct method is needed for the proof of the compatibility of the arithmetical axioms. The axioms of arithmetic are essentially nothing else than the known rules of calculation, with the addition of the axiom of continuity. I recently collected them and in so doing replaced the axiom of continuity by two simpler axioms, namely, the well-known axiom of Archimedes, and a new axiom essentially as follows: that numbers form a system of things which is capable of no further extension, as long as all the other axioms hold (axiom of completeness). I am convinced that it must be possible to find a direct proof for the compatibility of the arithmetical axioms, by means of a careful study and suitable modification of the known methods of reasoning in the theory of irrational numbers.

To show the significance of the problem from another point of view, I add the following observation: If contradictory attributes be assigned to a concept, I say, that mathematically the concept does not exist. So, for example, a real number whose square is -1 does not exist mathematically. But if it can be proved that the attributes assigned to the concept can never lead to a contradiction by the application of a finite number of logical processes, I say that the mathematical existence of the concept (for example, of a number or a function which satisfies certain conditions) is thereby proved. In the case before us, where we are concerned with the axioms of real numbers in arithmetic, the proof of the compatibility of the axioms is at the same time the proof of the mathematical existence of the complete system of real numbers or of the continuum. Indeed, when the proof for the compatibility of the axioms shall be fully accomplished, the doubts which have been expressed occasionally as to the existence of the complete system of real numbers will become totally groundless. The totality of real numbers, i. e., the continuum according to the point of view just indicated, is not the totality of all possible series in decimal fractions, or of all possible laws according to which the elements of a fundamental sequence may proceed. It is rather a system of things whose mutual relations are governed by the axioms set up and for which all propositions, and only these, are true which can be derived from the axioms by a finite number of logical processes. In my opinion, the concept of the continuum is strictly logically tenable in this sense only. It seems to me, indeed, that this corresponds best also to what experience and intuition tell us. The concept of the continuum or even that of the system of all functions exists, then, in exactly the same sense as the system of integral rational numbers, for example, or as Cantor's higher classes of numbers and cardinal numbers. For I am convinced that the existence of the latter, just as that of the continuum, can be proved in the sense I have described; unlike the system of all cardinal numbers or of all Cantor's alephs, for which, as may be shown, a system of axioms, compatible in my sense, cannot be set up. Either of these systems is, therefore, according to my terminology, mathematically non-existent.



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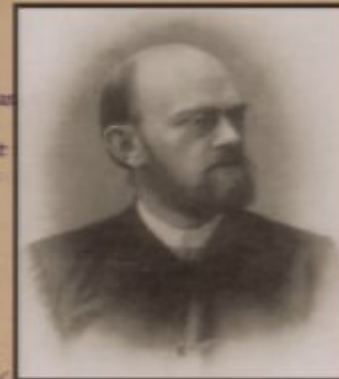
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But above all I wish to designate the following as the most important among the numerous questions which can be asked with regard to the axioms: To prove that they are not contradictory, that is, that a definite number of logical steps based upon them can never lead to contradictory results.

In geometry, the proof of the compatibility of the axioms can be effected by constructing a suitable field of numbers, such that analogous relations between the numbers of this field correspond to the geometrical axioms. Any contradiction in the deductions from the geometrical axioms must then upon be recognizable in the arithmetic of this field of numbers. In this way the desired proof for the compatibility of the geometrical axioms is made to depend upon the theorem of the compatibility of the arithmetical axioms.

On the other hand a direct method is needed for the proof of the compatibility of the arithmetical axioms. The axioms of arithmetic are essentially nothing else than the known rules of calculation, with the addition of the axiom of continuity. I recently collected them; and in so doing replaced the axiom of continuity by two simpler axioms, namely, the well-known axiom of Archimedes, and a new axiom essentially as follows: that numbers form a system of things which is capable of no further extension, as long as all the other axioms hold (axiom of completeness). I am convinced that it must be possible to find a direct proof for the compatibility of the arithmetical axioms, by means of a careful study and suitable modification of the known methods of reasoning in the theory of irrational numbers.

To show the significance of the problem from another point of view, I add the following observation: If contradictory attributes be assigned to a concept, I say, that mathematically the concept does not exist. So, for example, a real number whose square is -1 does not exist mathematically. But if it can be proved that the attributes assigned to the concept can never lead to a contradiction by the application of a finite number of logical processes, I say that the mathematical existence of the concept (for example, of a number or a function which satisfies certain conditions) is thereby proved. In the case before us, where we are concerned with the axioms of real numbers in arithmetic, the proof of the compatibility of the axioms is at the same time the proof of the mathematical



This statement is false

and intuition tell us. The concept of the continuum or even that of the system of all functions exists, then, in exactly the same sense as the system of integral rational numbers, for example, or as Cantor's higher classes of numbers and cardinal numbers. For I am convinced that the existence of the latter, just as that of the continuum, can be proved in the sense I have described, unlike the system of all cardinal numbers or of all Cantor's alephs, for which, as may be shown, a system of axioms, compatible in my sense, cannot be set up. Either of these systems is, therefore, according to my terminology, mathematically non-existent.

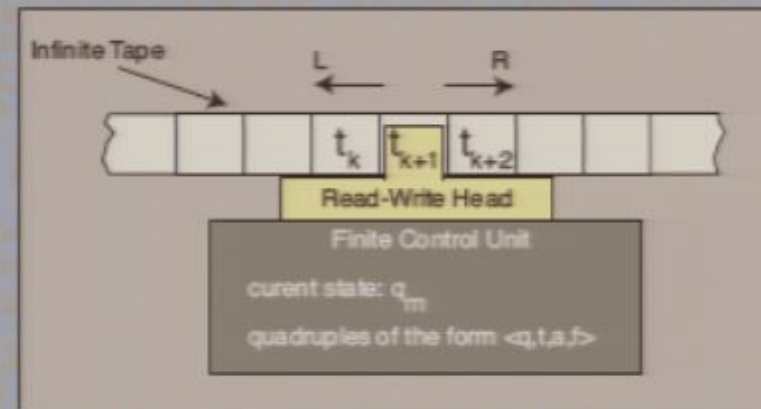
Turing machines



Church



Turing



Turing machine

"We can only see
a short distance ahead,
but we can see plenty there
that needs to be done."

Alan Turing

Complexity theory

Goal: asses the amount of ressources to solve problems

→ Adding: $748230 + 3802 = 752032$

Scale is number of digit of input

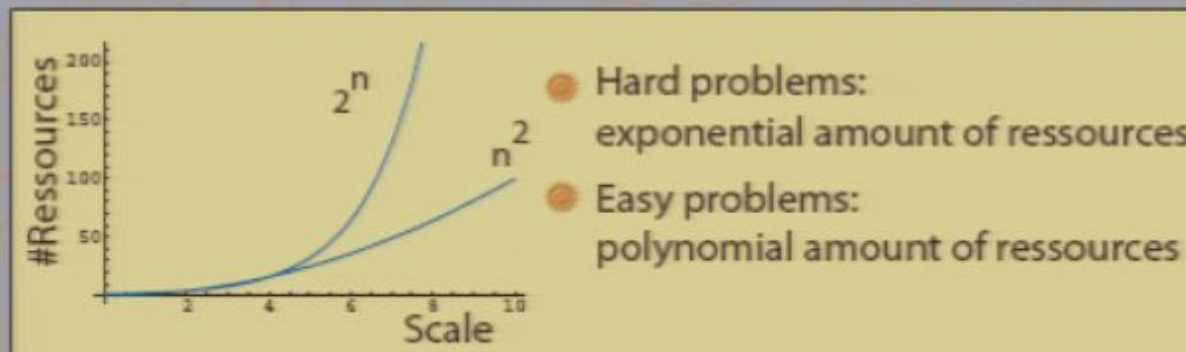
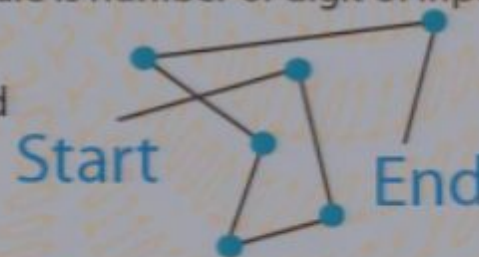
→ Factor in product of primes: $54029 = 97 \times 557$

Scale is number of digit of input

→ Travelling salesperson:

Find the shortest route from Start to End

Scale is number of cities



Strong Church Turing principle:
no machine can turn a hard problem into an easy one

Quantum Factoring



Peter Shor

(Shor, IEEE Press 1994)

$$n=pq \quad (L = \ln n)$$

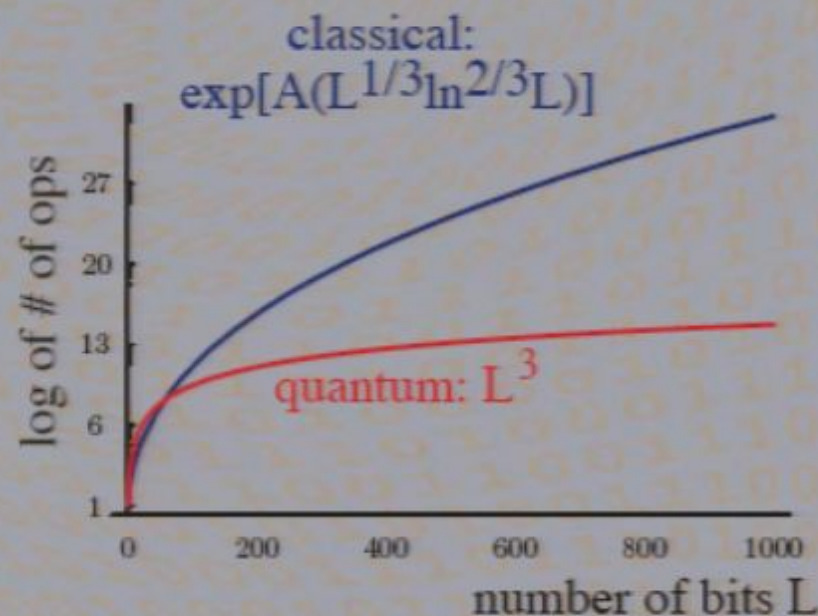
+

Today the fastest classical computers
can factor number with ~150 digits

Quantum algorithm

of gates $\sim 12L^3$

of qubits $\sim 5L$



A classical computer in a nutshell

- Classical bits of information are encoded in physical systems which has two states 0 and 1

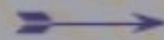
...110		...001
01000	$\Rightarrow + \Rightarrow$	01100
11101		00101
000...		010...

- Transformations are made with (universal) gates

Not Gate
And Gate

1 $\Rightarrow$ 0 or 0 $\Rightarrow$ 1

Input 1



Output

Input 2

Input 1 And Input 2

0	0	0
1	0	0
0	1	0
1	1	1

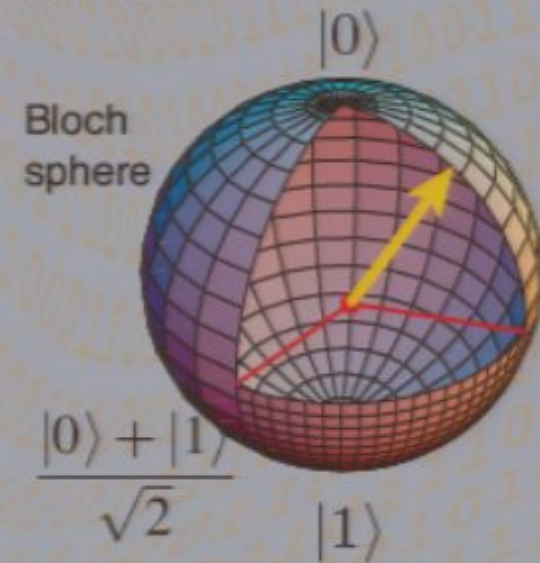
in out

A quantum computer in a nutshell

Quantum bits (qubits) are quantum systems with two levels

$$\text{red sphere with up arrow} = 0.95 \left(\text{red sphere with up arrow} = 1 \right) + 0.3 \left(\text{red sphere with down arrow} = 0 \right)$$

$$\text{elliptical orbit with 4 dots} = 0.95 \left(\text{elliptical orbit with 4 dots} \right) + 0.3 \left(\text{elliptical orbit with 4 dots} \right)$$



Universal set of operations (gates)

- generic one bit gates
- any interaction between qubits

A classical computer in a nutshell

- Classical bits of information are encoded in physical systems which has two states 0 and 1

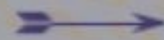
...110	→	...001
01000		01100
11101		00101
000...		010...

- Transformations are made with (universal) gates

Not Gate
And Gate

1 → 0 or 0 → 1

Input 1



Output

Input 2

Input 1 And Input 2

0	0	0
1	0	0
0	1	0
1	1	1

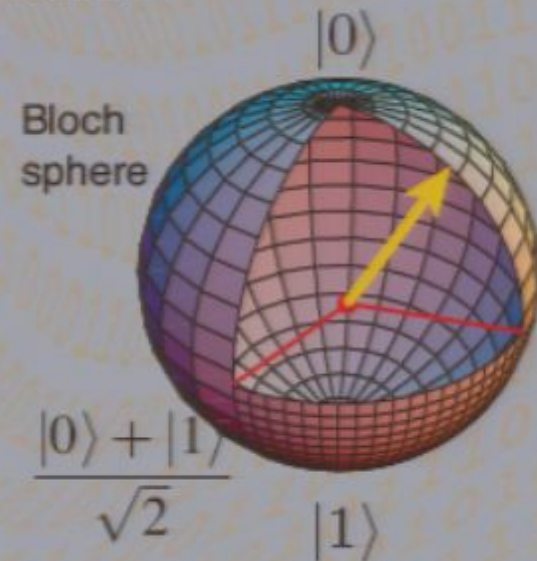
in out

A quantum computer in a nutshell

Quantum bits (qubits) are quantum systems with two levels

$$\text{qubit} = 0.95 \left(\text{spin up} = 1 \right) + 0.3 \left(\text{spin down} = 0 \right)$$

$$\text{atom} = 0.95 \left(\text{orbital 1} \right) + 0.3 \left(\text{orbital 2} \right)$$



Universal set of operations (gates)
-generic one bit gates
-any interaction between qubits

The power of Quantum Computers

of quantum
bits

1



quantum states

0,1



A quantum bit
can be in two states
at the same time

of classical
bits

$2^1=2$



We need two parameters to describe the state

The power of Quantum Computers

of quantum bits

1



2



quantum states

0,1

00,01,10,11



Two quantum bit
can be in four states
at the same time

of classical bits

$2^1=2$

$2^2=4$



We need four parameters to describe the state

The power of Quantum Computers

of quantum
bits

1



2



3



quantum states

0,1

00,01,10,11

000,001,...,111

of classical
bits

$2^1=2$

$2^2=4$

$2^3=8$

The power of Quantum Computers

of quantum
bits

quantum states

of classical
bits

1



0,1

$2^1=2$

2



00,01,10,11

$2^2=4$

3



000,001,...,111

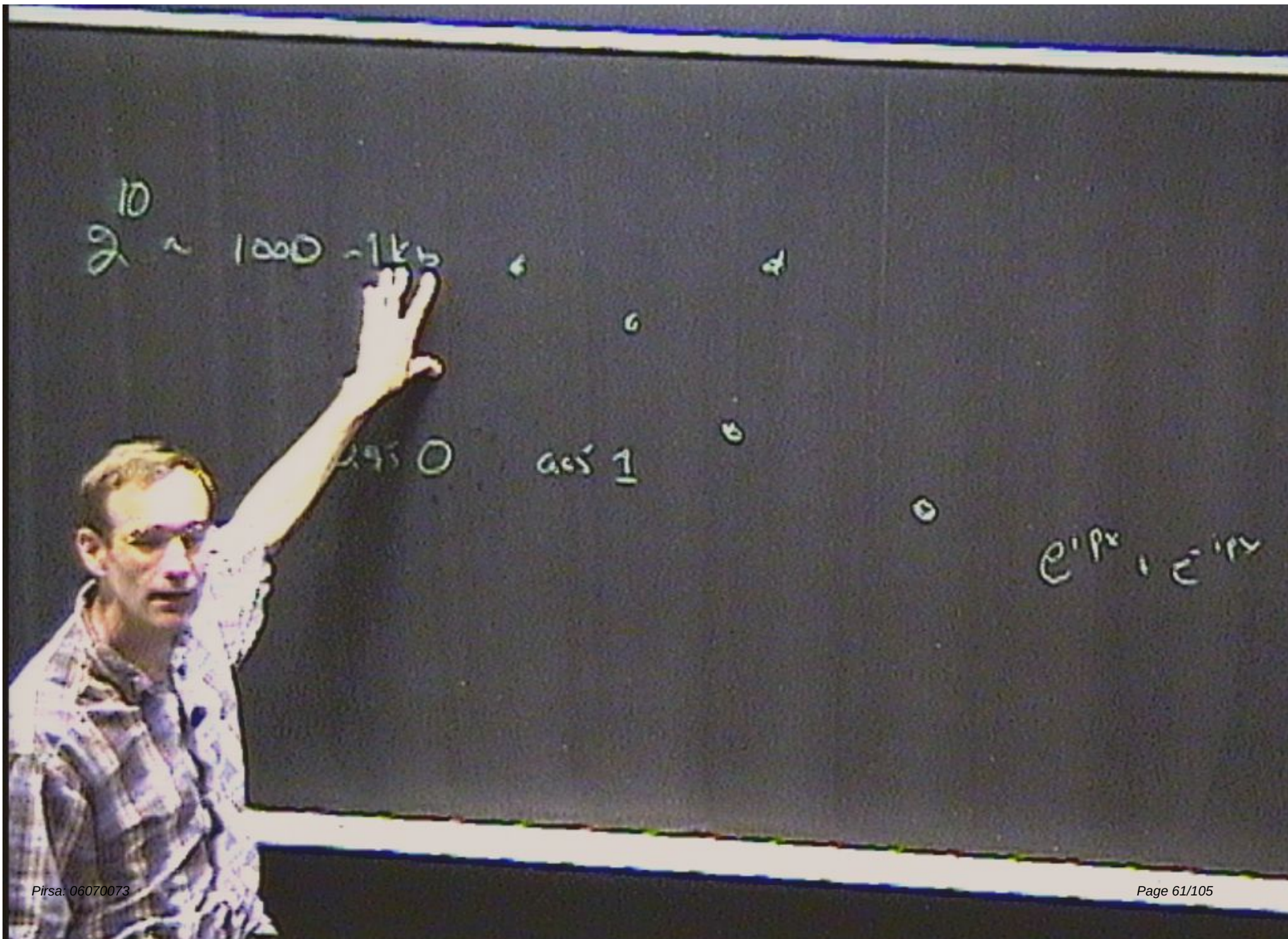
$2^3=8$

4



0000,0001,...,1111

$2^4=16$



10
2 ~ 1000 - 1 kb

2.95 0

acc 1

e^{12} , e^{12}

4

6

$e^{i\varphi}, e^{-i\varphi}$

10
 $2^1 \sim 1000 - 1kb$
 $2^{20} \sim 1M$
 $2^{30} \sim 1G$
 $2^{40} \sim 1T$ ~~style~~ $2^{40} \sim 1T$

e^{10^4} , e^{10^5}

10
 $2 \sim 1000 - 1kb$
 $2^{20} \sim 1M$
 $2^{30} \sim 1G$
 $2^{40} \sim 1T$ $2^{45} \sim 1P$
 $2^{50} \sim 1P$
 $2^{60} \sim$

e^{12x}, e^{-12x}

10

20

30

40

50

60

70

80

1000

100

10

1000

1000

1000

10

10000 10000

10000

10000

10000

10000

10000

10		
2	~	1000 - 1 kb
20	~	1 M
200	~	1 G
240	~	1 Terabyte
250	~	1 Petabyte
260	~	↑

e.m.c.

The power of Quantum Computers

of quantum
bits

quantum states

of classical
bits

1



0,1

$2^1=2$

2



00,01,10,11

$2^2=4$

3



000,001,...,111

$2^3=8$

4



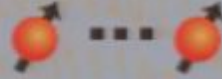
0000,0001,...,1111

$2^4=16$

⋮

⋮

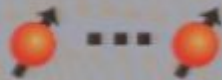
10



0000000000,...

$2^{10}=1k$

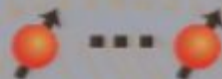
20



0000000000...,

$2^{20}=1M$

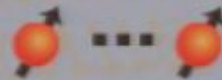
30



0000000000...,

$2^{30}=1G$

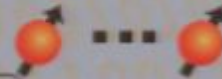
40



0000000000...,

$2^{40}=1T$

50



0000000000...,

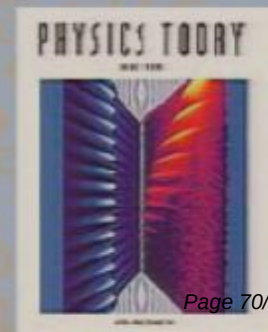
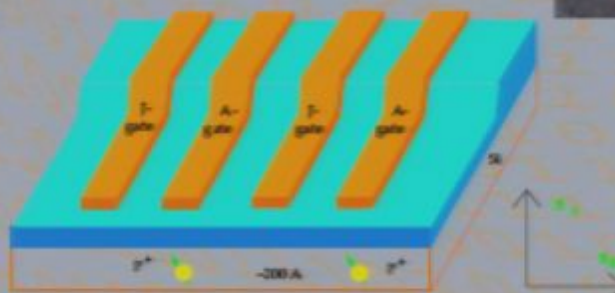
$2^{50}=1P$

Theory vs experiment



Devices for QIP

- Atom traps
- Cavity QED
- Electron floating on helium
- Electron trapped by surface acoustic waves
- Ion trap
- Nuclear Magnetic Resonance
- Quantum dots
- Quantum optics
- Solid state
- Spintronics
- Superconducting Josephson junctions



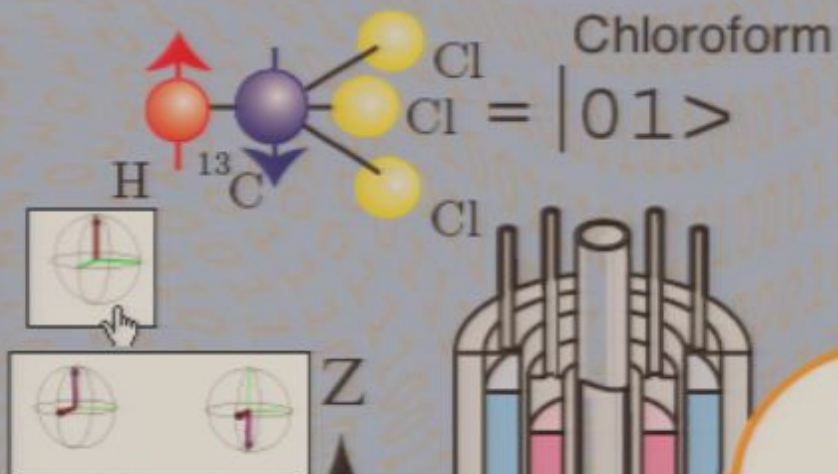
Nuclear Magnetic Resonance



Bloch



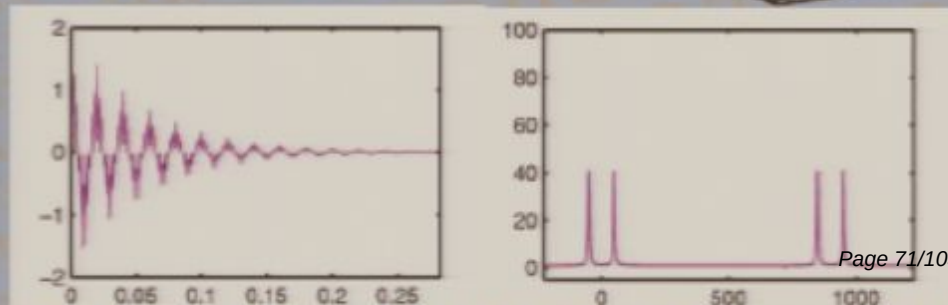
Purcell



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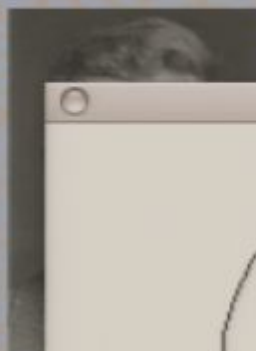
Bruker 700



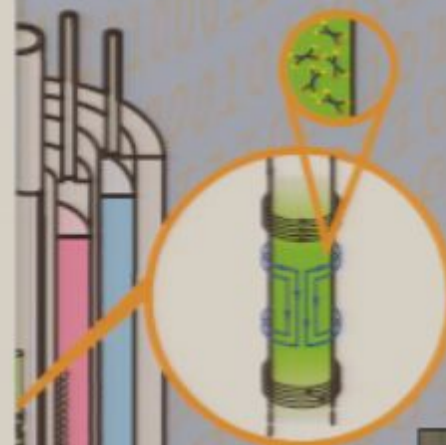
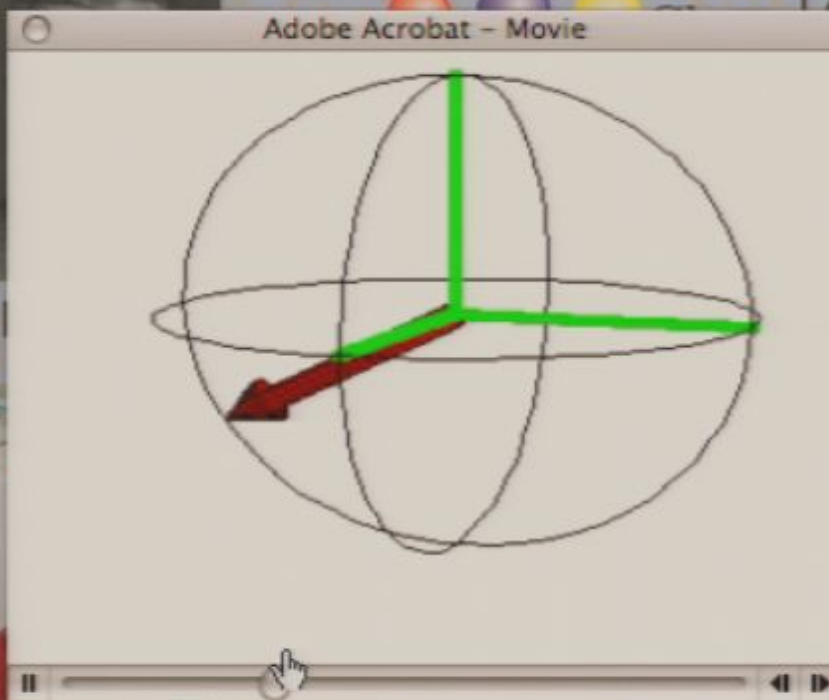
Nuclear Magnetic Resonance



Bloch



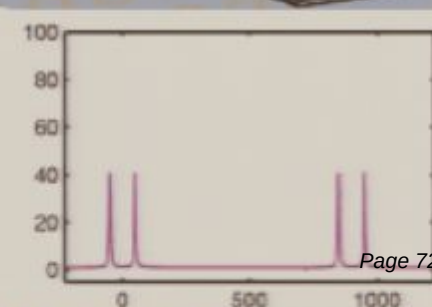
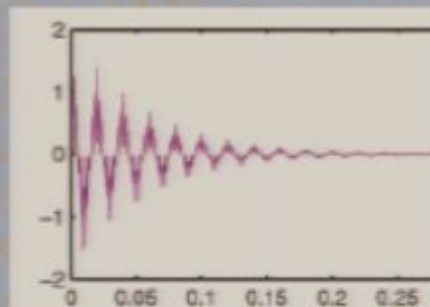
Chloroform



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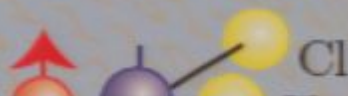
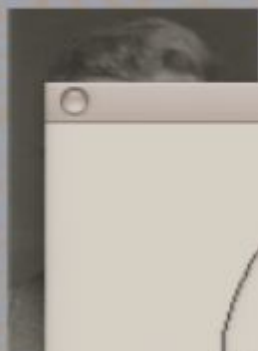
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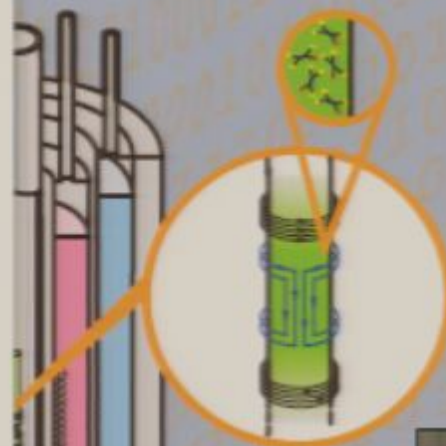
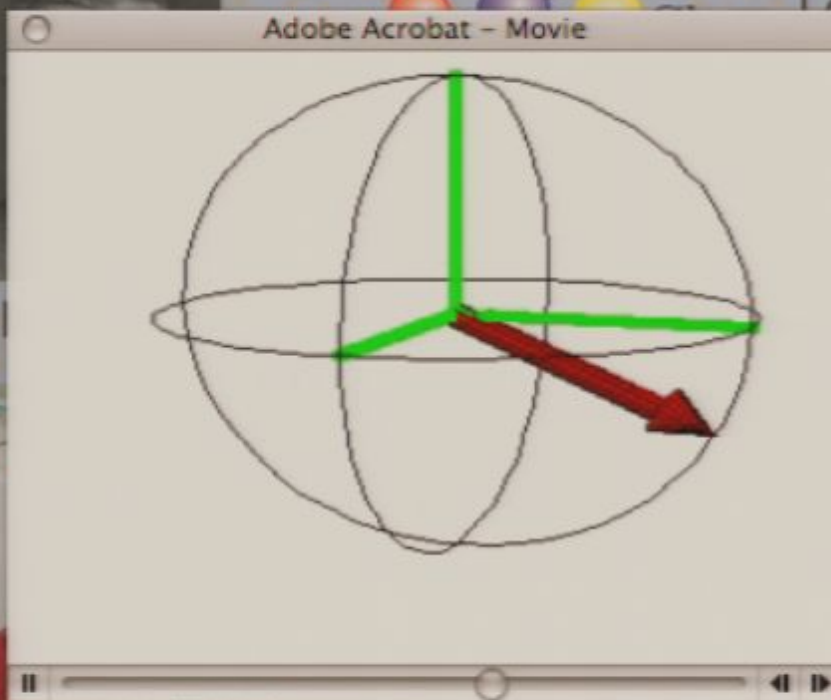
Nuclear Magnetic Resonance



Bloch



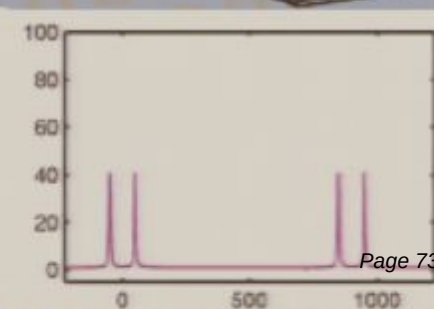
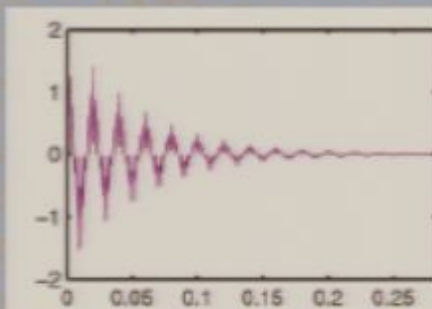
Chloroform



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Bruker 700



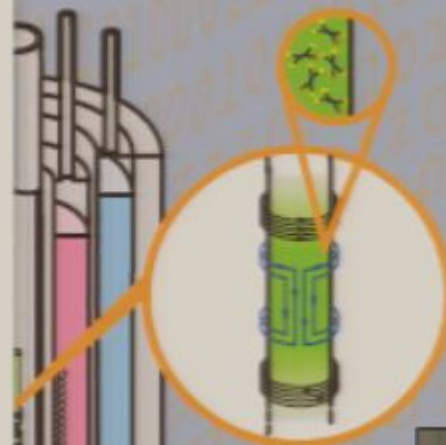
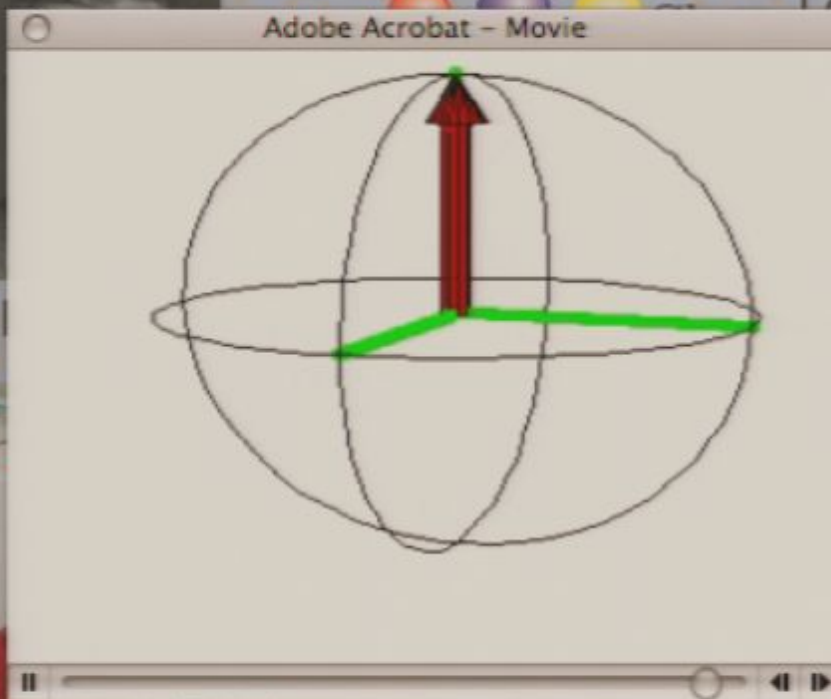
Nuclear Magnetic Resonance



Bloch



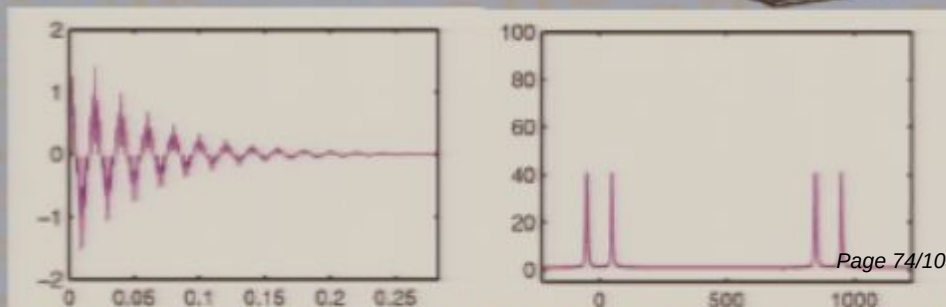
Chloroform



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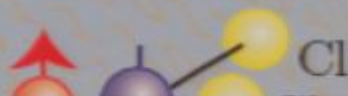
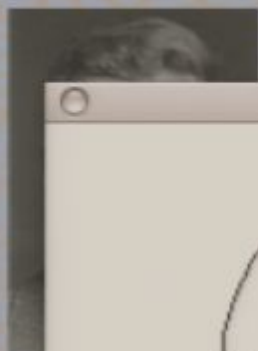
Bruker 700



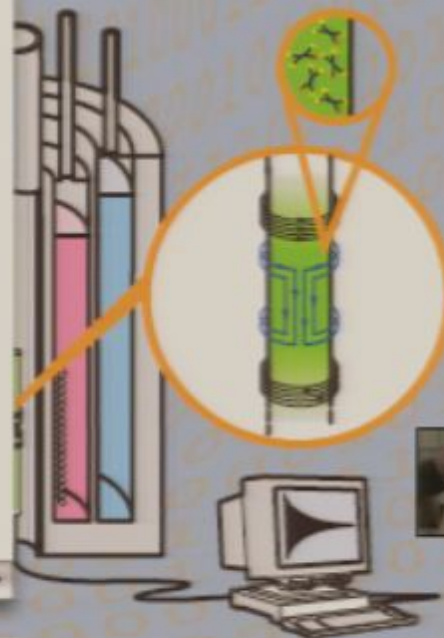
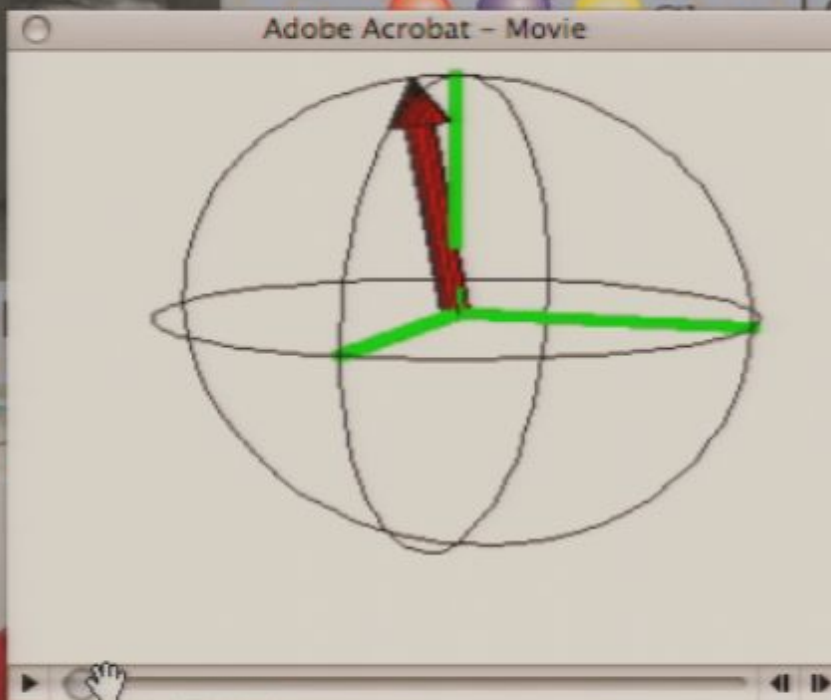
Nuclear Magnetic Resonance



Bloch



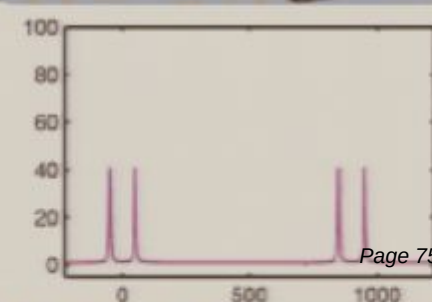
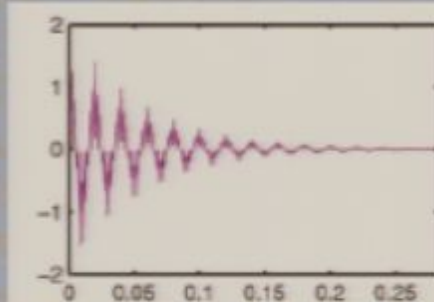
Chloroform



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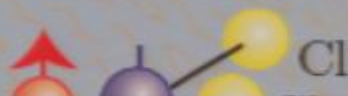
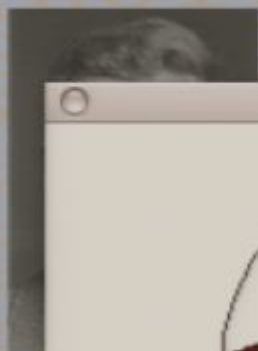
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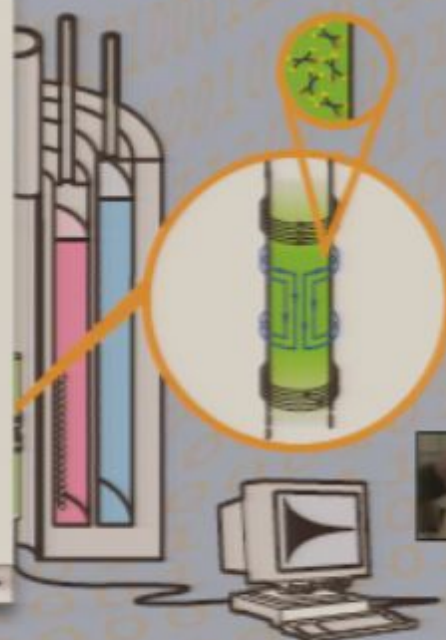
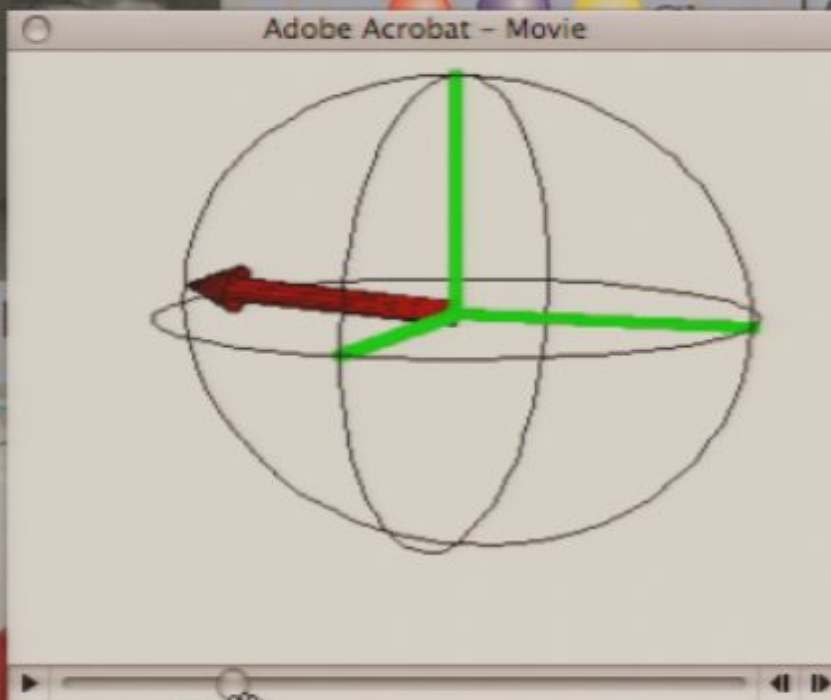
Nuclear Magnetic Resonance



Bloch



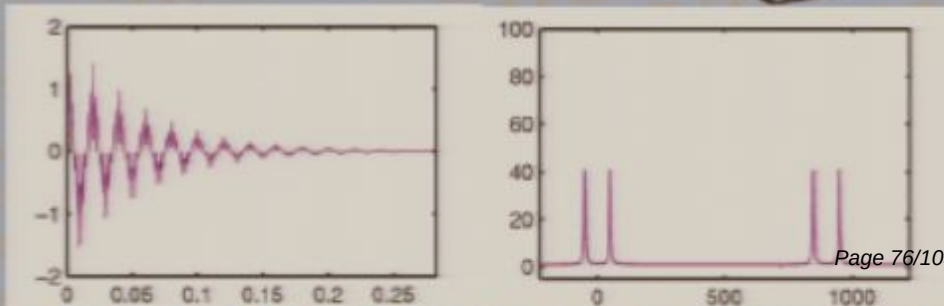
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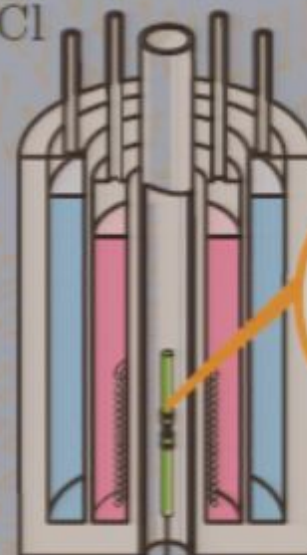
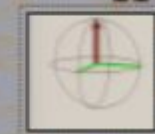
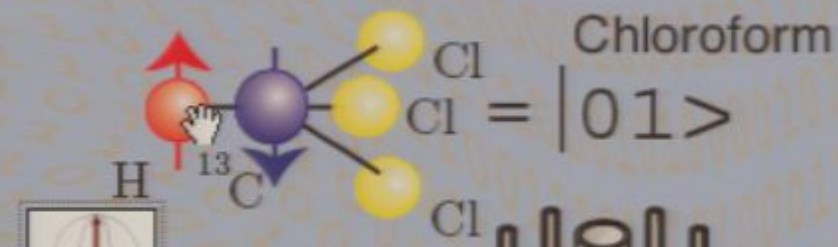
Nuclear Magnetic Resonance



Bloch



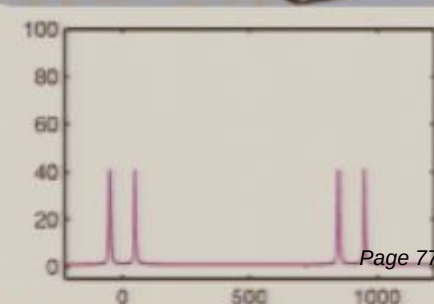
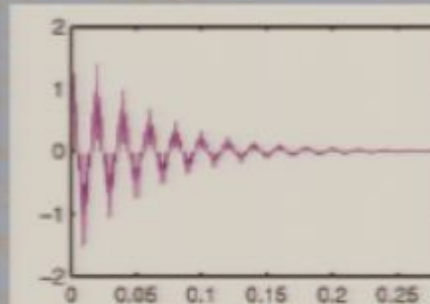
Purcell

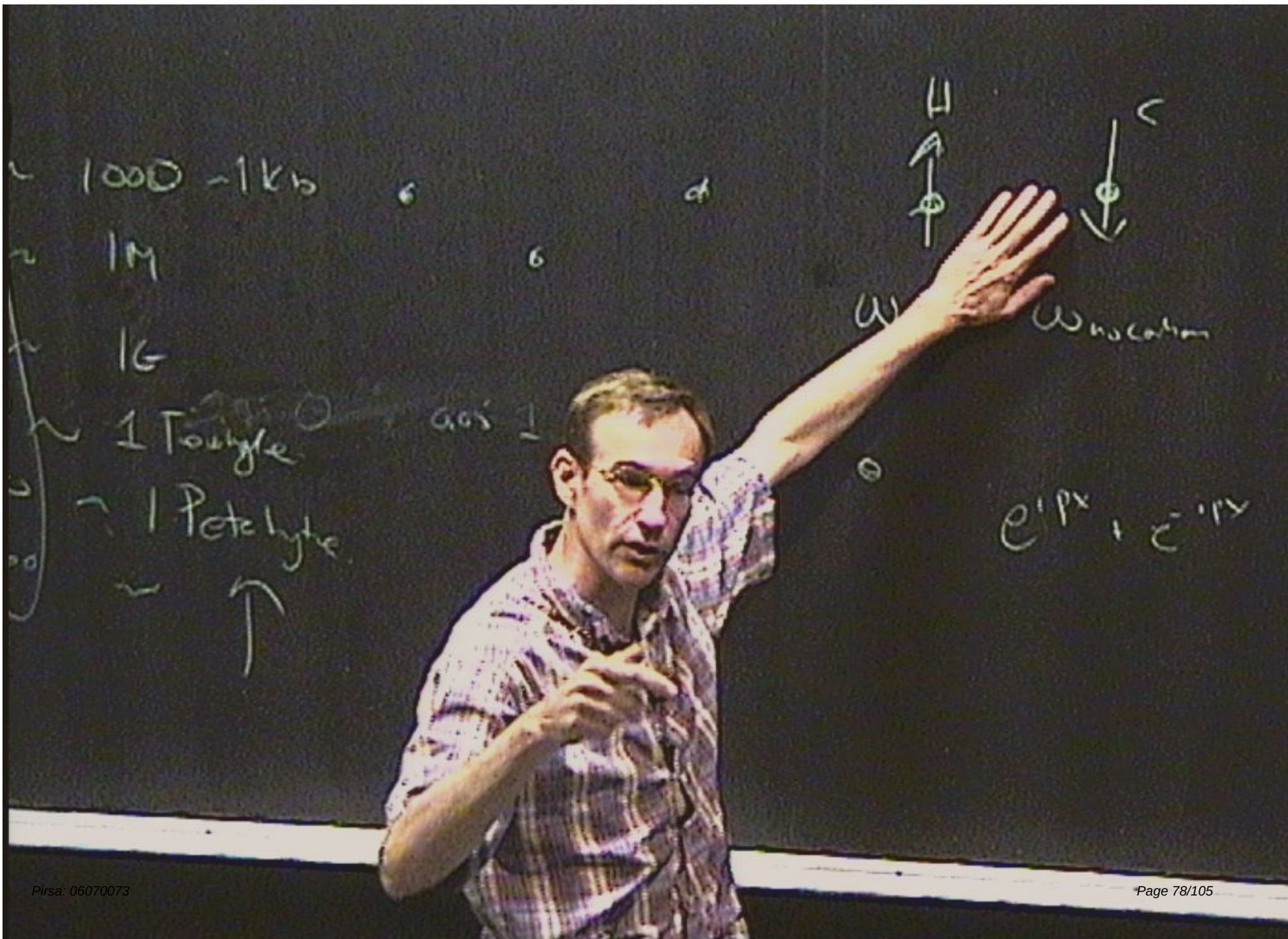


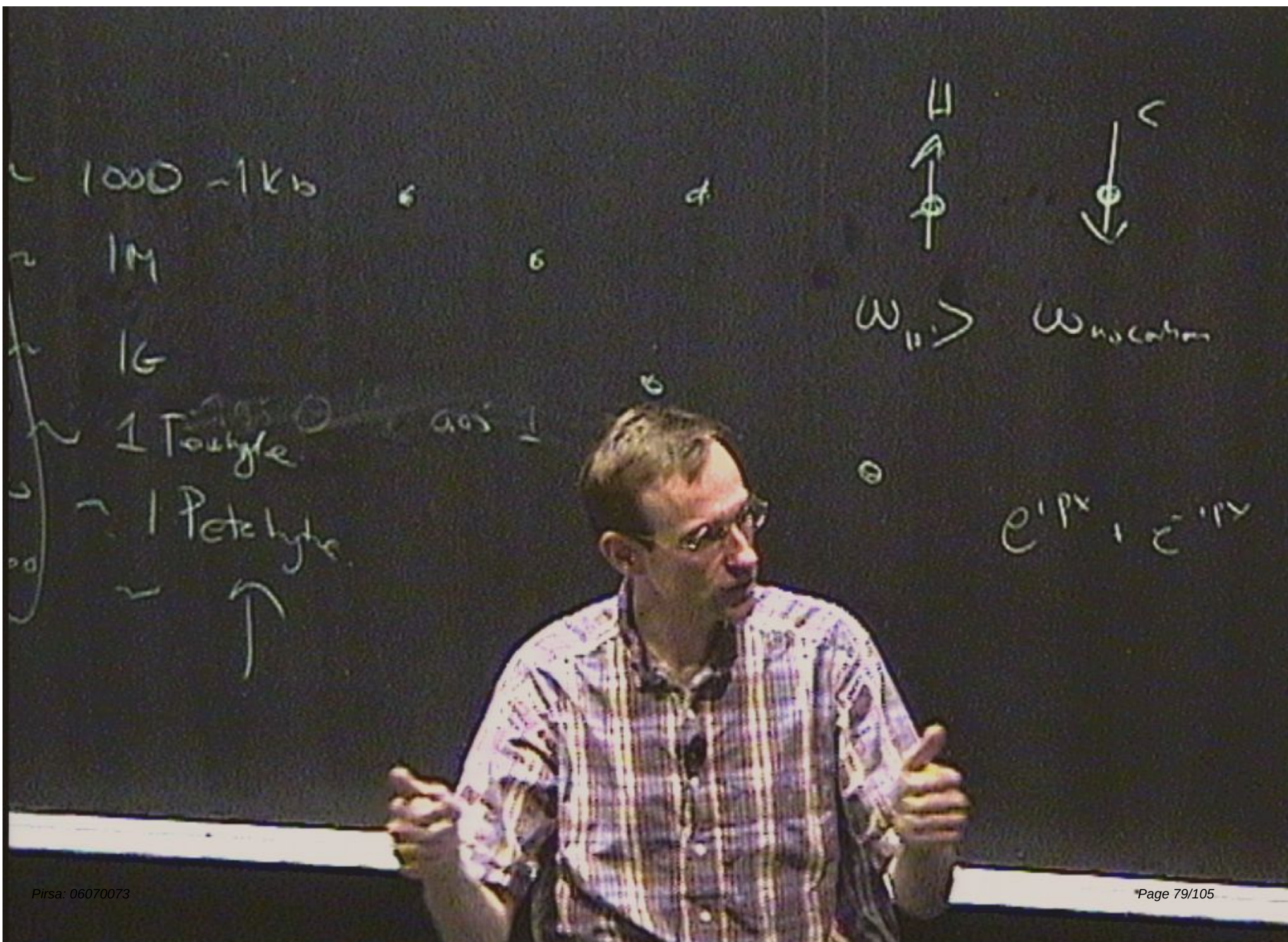
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1000-1kb

1M

1G

1 TeraByte

1 PetaByte

↑



$\omega_{||} >$



$\omega_{||} <$

$e^{i p x}$, $e^{-i p x}$

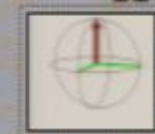
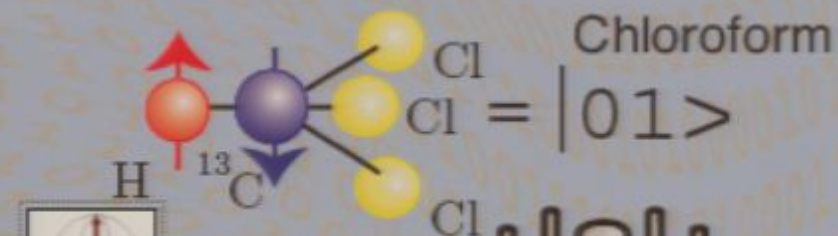
Nuclear Magnetic Resonance



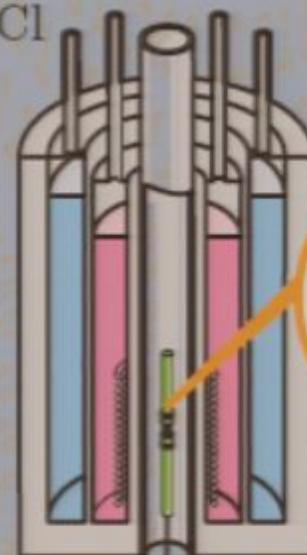
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Purcell



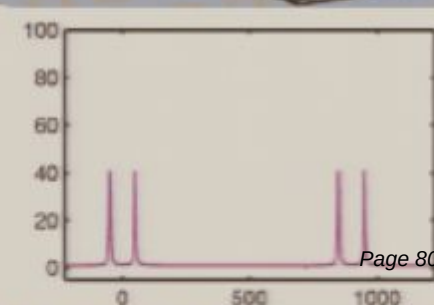
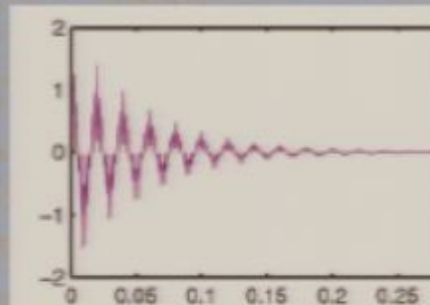
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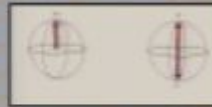
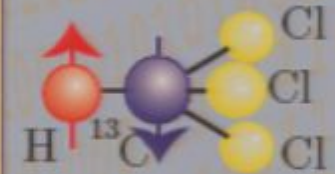
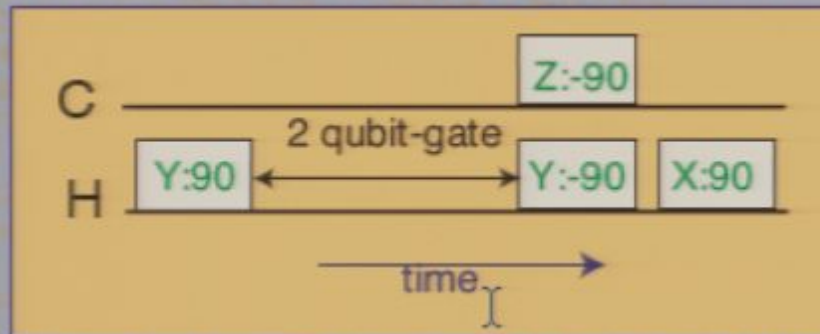
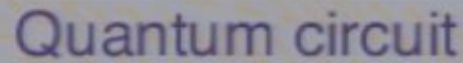
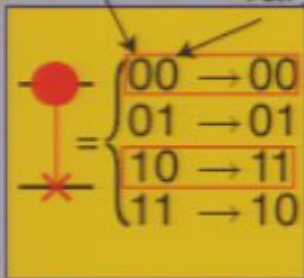
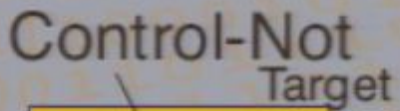


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Pre-compiler (Optimizer)

Braker (machine) language

```
;; retry to track down error sources by doing partial error correction.

(define cube
  (search(es) = 1)
  (search(es) = 2)
  (include "cnp.h")

  > glommg = 1; glomtz = 2; gl

  ; scale .1
  1/*
  1/* glommg = 1; glomz
  pulse cnp seed-10
  ; correction steps
  1/*
  1/*
  (cnp cz -cz)
  ; zz .25 C1 C
  (pulse cz 90
   zz .25 C1 C)
  (pulse w-.75)
  ; zpulse C1:.
  (pulse cz 90
   (pulse cz 90
    become flux))
  ; pulse C2_90
  delay end 1
  ;
  ; pulse C2_90
  ;
  (include "test_def"
   refocus C1C
```

```
; pulse C2_90 .25
; zz .25 C1 C2
; zpulse C1:.75;C2:
; pulse C2_90 .75
; pulse C2_90 .0
refocus C1C2 180
```

```

1  <
2  Should become zero
3
4
5  Should become one
6
7  Initial virtual zero
8  Value 0.000000 second
9
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(C2_90:sp9 ph13 ):f1
3u_
3u ipp13

0.71365m

8u
8u
(C2_90:sp9 ph19):f1
6u_ipp15 ipp19
8u
(C2_90:sp9 ph20):f1
6u_ipp15 ipp20
```

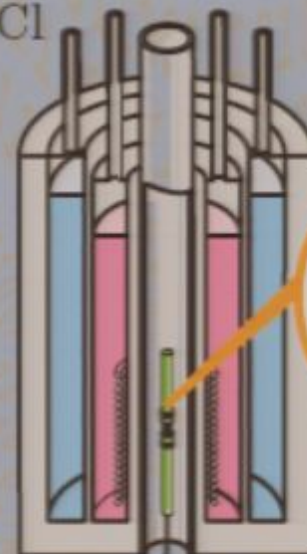
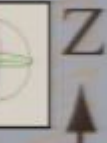
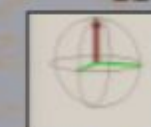
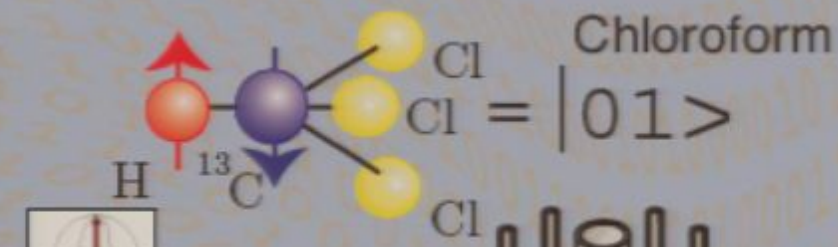

Nuclear Magnetic Resonance



Bloch



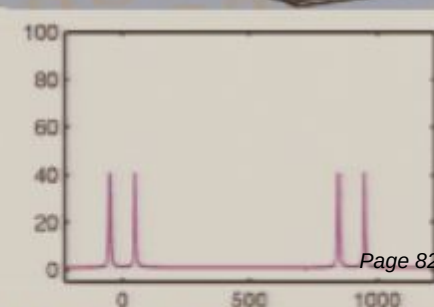
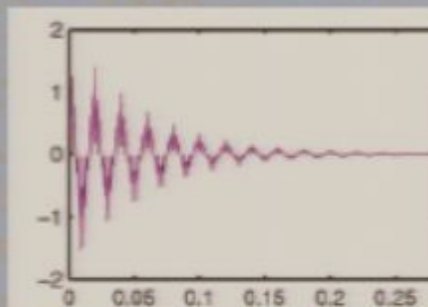
Purcell



University of
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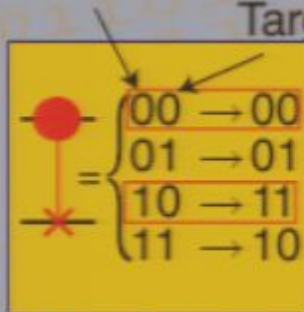


Bruker 700

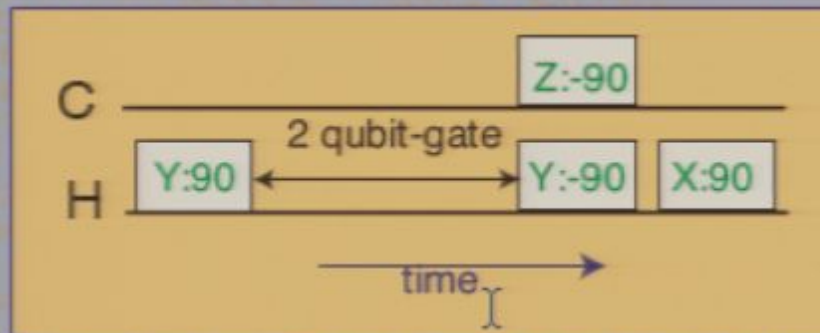


Quantum algorithms 101: the Control-NOT

Control-Not



Quantum circuit

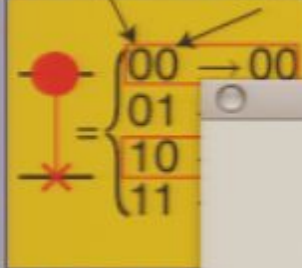
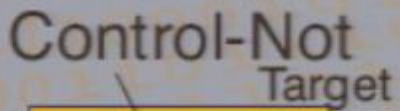


Pre-compiler (Optimizer)

Bruker (machine) language

```
;; retry to track down error sources by doing partial error correction.
(define-cube
  (switch(w1) = 1)
  (switch(w2) = 1)
  (include "cnp.h")
  (slowmg = 1; slowtp = 2; sl)
  (scale .1
    (slowmg = 1; slowtp
      (pulse-loop w1 w2)
      (correction-stage)
      (cnp)
      (pulse-c2 90
        (z .25 C1 C2)
        (zpulse C1:.75;C2:
          (pulse C2_90 .75)
          (pulse C2_90 .0)
          refocus C1C2_180
```

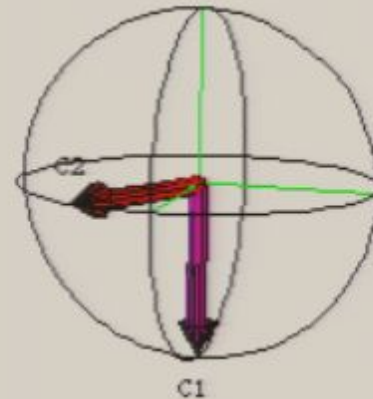
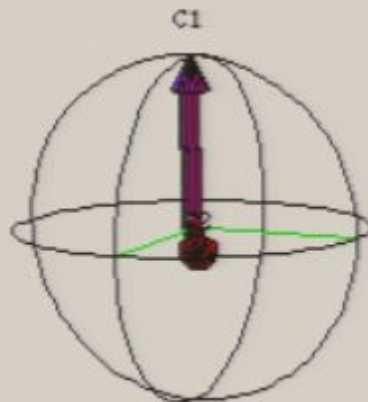
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97. 130d1 130m1 130m2
98. 130d1 130m1 130m2
99. 130d1 130m1 130m2
100. 130d1 130m1 130m2
```

Quantum circuit



Adobe Acrobat – Movie



Pre-

[illegible]

```
; zz .25 C1 C2
; zpulse C1:.75;C2:
; pulse C2_90 .75
; pulse C2_90 .0
refocus C1C2 180
```

0.71365m

8u

8u

(C2 90:sp9 ph19):f1

6u⁻ipp15 ipp19

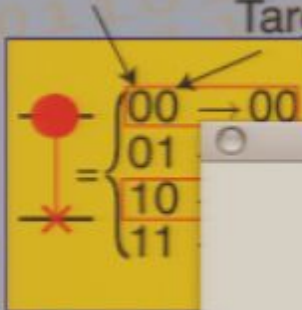
8u

(C2 90:sp9 ph20):f1

6u-ipp15 ipp20

Control-Not
Target

Quantum circuit



C

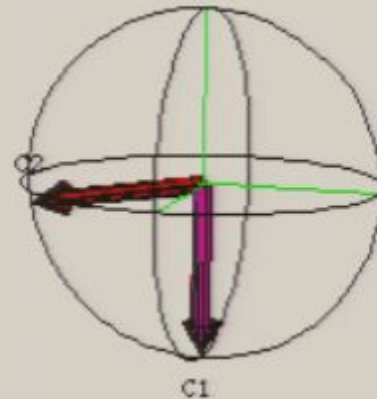
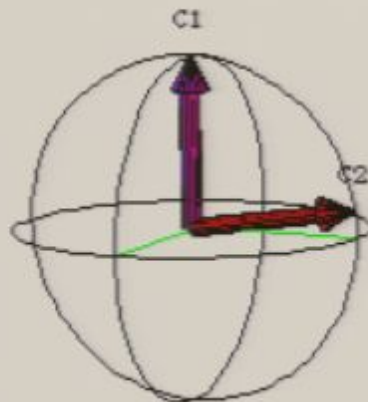
Z:-90

Adobe Acrobat – Movie

Cl

Cl

Cl



Pre-

```

1.2 return to top
1.3
1.4 define crate
1.5 {
1.6   {watch(wz) = 1
1.7   {watch(wz) = 2
1.8   {update "crrp"
1.9 }
2.0 }
2.1
2.2 crate 1
2.3
2.4 {
2.5   {slowing = 0
2.6   {pulse stop at
2.7   {correction at
2.8 }
2.9 }
3.0
3.1 {
3.2   {pulse on so
3.3   {in use on so
3.4   {pulse on so
3.5   {pulse on so
3.6   {pulse on so
3.7   {before stop
3.8 }
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```

```
; zz .25 C1 C2
; zpulse C1:.75;C2:
; pulse C2_90 .75
; pulse C2_90 .0
refocus C1C2 180
```

0.71365m

8u

84

(C2 90:sp9 ph19):f1

6u-ipp15 ipp19

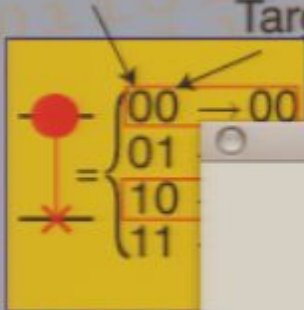
8u

(C2 90:sp9 ph20):f1

6u-ipp15 ipp20

Control-Not Target

Quantum circuit



C

Z:-90

Adobe Acrobat – Movie

C2

C1

Pre-

```

12 return to top
define cube
13 search [0 1] = 1
14 search [0 1] = 1
15 search [0 1] = 1
16 glomming = 1
17
18 scale .1
19 glomming = 1
20 pulse loop on
21 correction on
22
23 count 10000
24 pulse 10 10
25 10 10 10
26 pulse 10 10
27 pulse 10 10
28 pulse 10 10
29 become 100
30
31 delay end
32
33 glomming = 1

```

```
; zz .25 C1 C2
; zpulse C1:.75;C2:
; pulse C2_90 .75
; pulse C2_90 .0
refocus C1C2 180
```

0.71365m

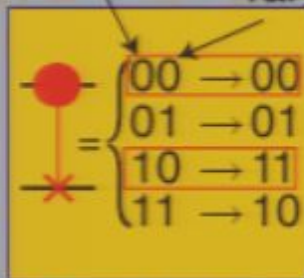
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8u
8u
(C2_90:sp9 ph19):f1
6u-ipp15 ipp19
8u
(C2_90:sp9 ph20):f1
6u-ipp15 ipp20

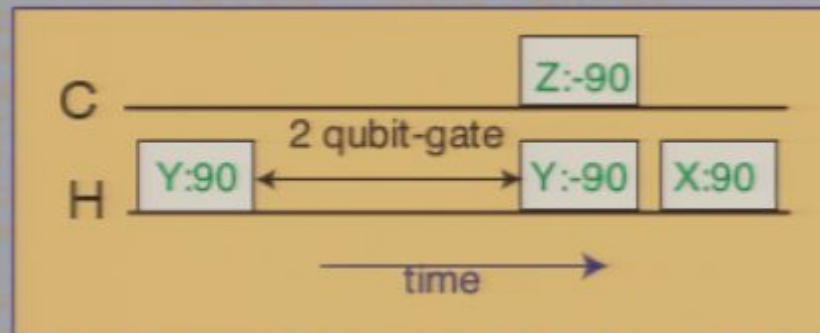
```

Pirsa: 06070073

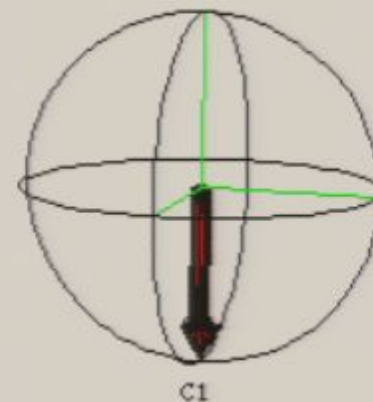
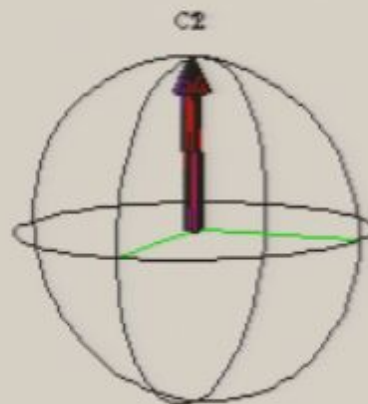
Control-Not Target



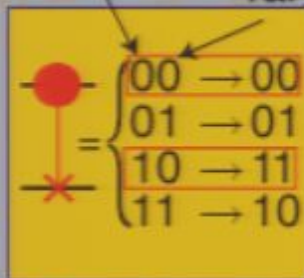
Quantum circuit



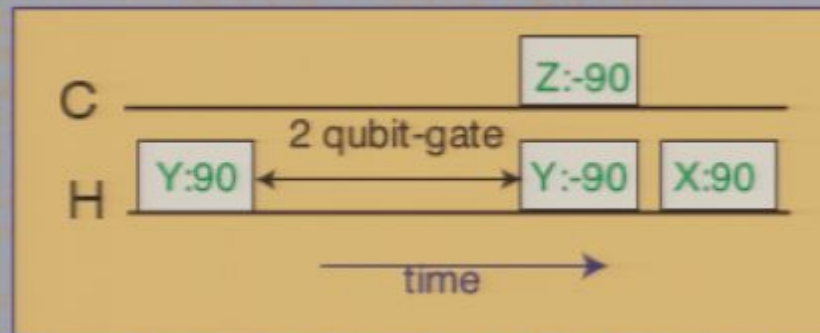
Adobe Acrobat – Movie



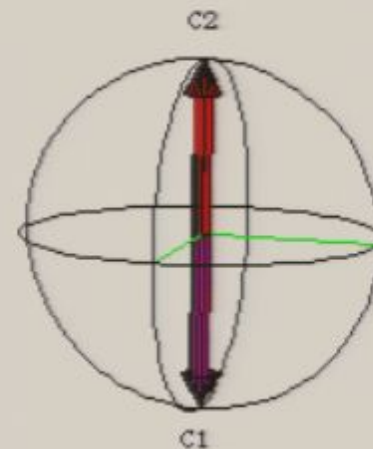
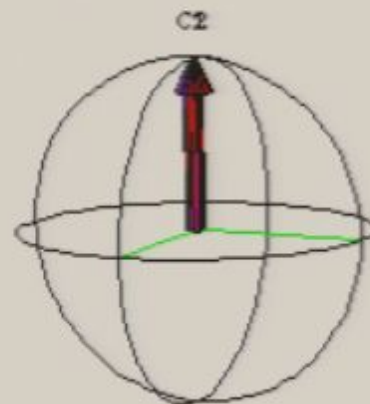
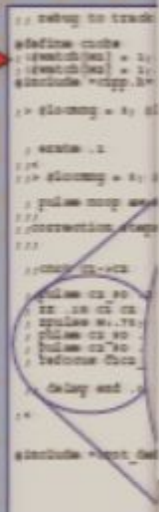
Control-Not Target

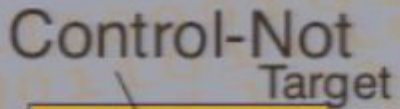


Quantum circuit

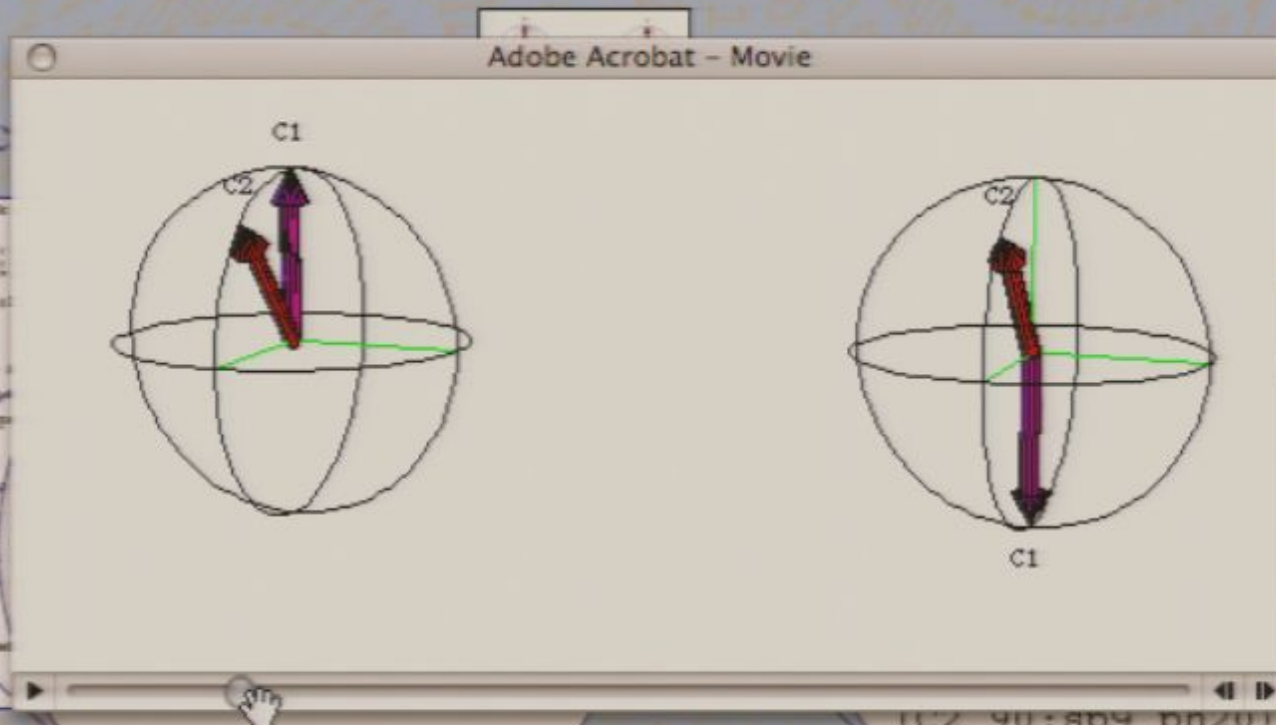
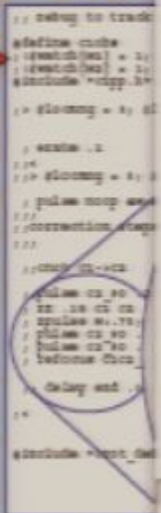
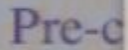
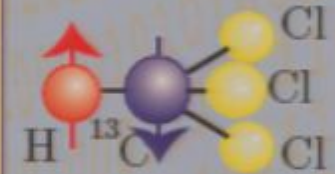
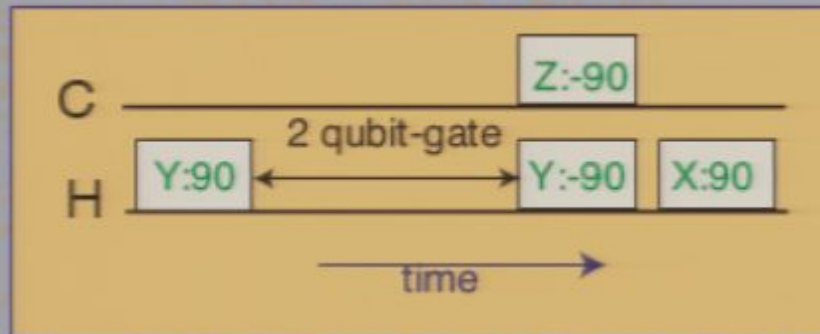
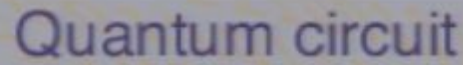


Pre-c



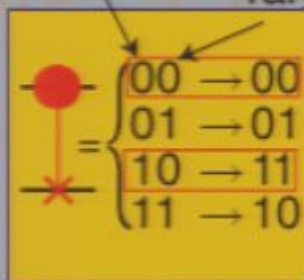




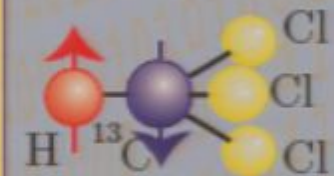
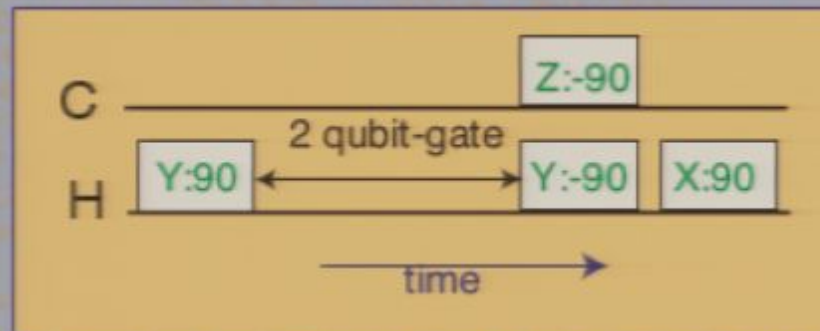


Quantum algorithms 101: the Control-NOT

Control-Not
Target



Quantum circuit

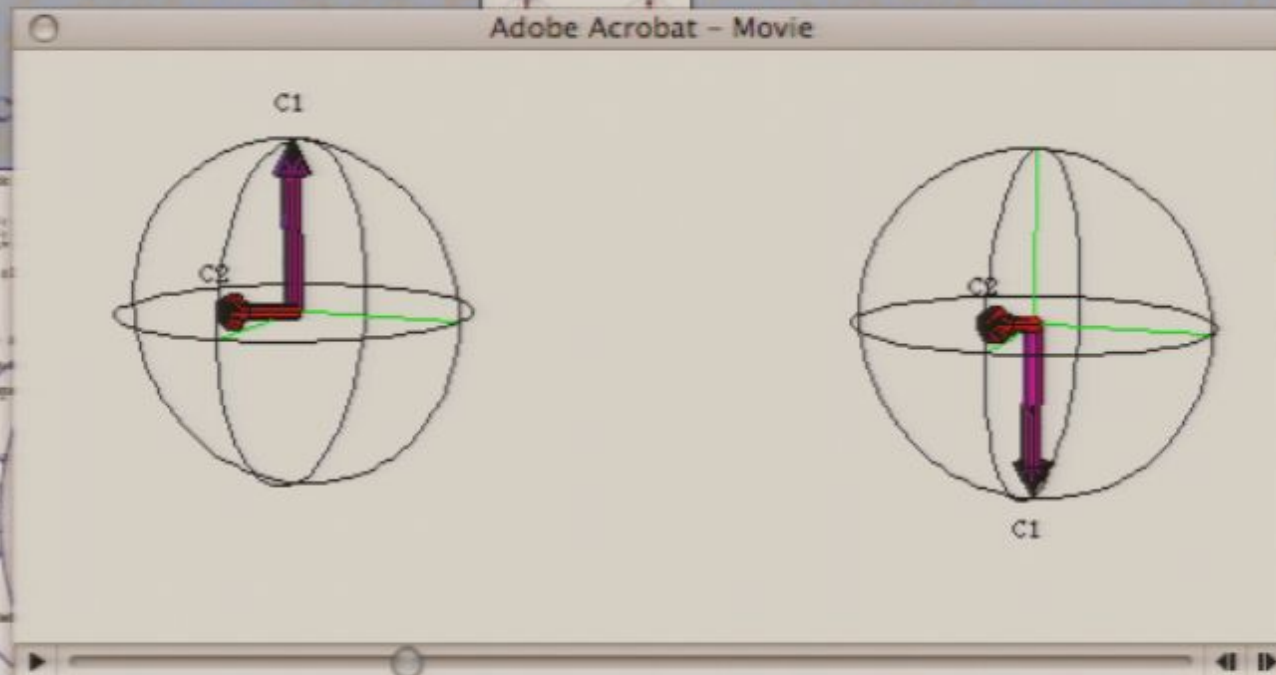


Pre-c

```

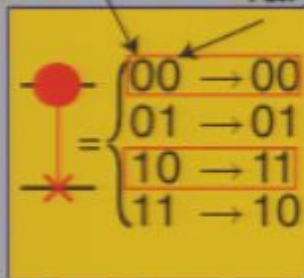
1: return to trade
2: define cube
3: (x1,x2,x3) = 1;
4: (x4,x5,x6) = 1;
5: (x7,x8,x9) = 1;
6: (x10,x11,x12) = 1;
7: (x13,x14,x15) = 1;
8: (x16,x17,x18) = 1;
9: (x19,x20,x21) = 1;
10: (x22,x23,x24) = 1;
11: (x25,x26,x27) = 1;
12: (x28,x29,x30) = 1;
13: (x31,x32,x33) = 1;
14: (x34,x35,x36) = 1;
15: (x37,x38,x39) = 1;
16: (x40,x41,x42) = 1;
17: (x43,x44,x45) = 1;
18: (x46,x47,x48) = 1;
19: (x49,x50,x51) = 1;
20: (x52,x53,x54) = 1;
21: (x55,x56,x57) = 1;
22: (x58,x59,x60) = 1;
23: (x61,x62,x63) = 1;
24: (x64,x65,x66) = 1;
25: (x67,x68,x69) = 1;
26: (x70,x71,x72) = 1;
27: (x73,x74,x75) = 1;
28: (x76,x77,x78) = 1;
29: (x79,x80,x81) = 1;
30: (x82,x83,x84) = 1;
31: (x85,x86,x87) = 1;
32: (x88,x89,x90) = 1;
33: (x91,x92,x93) = 1;
34: (x94,x95,x96) = 1;
35: (x97,x98,x99) = 1;
36: (x100,x101,x102) = 1;
37: (x103,x104,x105) = 1;
38: (x106,x107,x108) = 1;
39: (x109,x110,x111) = 1;
40: (x112,x113,x114) = 1;
41: (x115,x116,x117) = 1;
42: (x118,x119,x120) = 1;
43: (x121,x122,x123) = 1;
44: (x124,x125,x126) = 1;
45: (x127,x128,x129) = 1;
46: (x130,x131,x132) = 1;
47: (x133,x134,x135) = 1;
48: (x136,x137,x138) = 1;
49: (x139,x140,x141) = 1;
50: (x142,x143,x144) = 1;
51: (x145,x146,x147) = 1;
52: (x148,x149,x150) = 1;
53: (x151,x152,x153) = 1;
54: (x154,x155,x156) = 1;
55: (x157,x158,x159) = 1;
56: (x160,x161,x162) = 1;
57: (x163,x164,x165) = 1;
58: (x166,x167,x168) = 1;
59: (x169,x170,x171) = 1;
60: (x172,x173,x174) = 1;
61: (x175,x176,x177) = 1;
62: (x178,x179,x180) = 1;
63: (x181,x182,x183) = 1;
64: (x184,x185,x186) = 1;
65: (x187,x188,x189) = 1;
66: (x190,x191,x192) = 1;
67: (x193,x194,x195) = 1;
68: (x196,x197,x198) = 1;
69: (x199,x200,x201) = 1;
70: (x202,x203,x204) = 1;
71: (x205,x206,x207) = 1;
72: (x208,x209,x210) = 1;
73: (x211,x212,x213) = 1;
74: (x214,x215,x216) = 1;
75: (x217,x218,x219) = 1;
76: (x220,x221,x222) = 1;
77: (x223,x224,x225) = 1;
78: (x226,x227,x228) = 1;
79: (x229,x230,x231) = 1;
80: (x232,x233,x234) = 1;
81: (x235,x236,x237) = 1;
82: (x238,x239,x240) = 1;
83: (x241,x242,x243) = 1;
84: (x244,x245,x246) = 1;
85: (x247,x248,x249) = 1;
86: (x250,x251,x252) = 1;
87: (x253,x254,x255) = 1;
88: (x256,x257,x258) = 1;
89: (x259,x260,x261) = 1;
90: (x262,x263,x264) = 1;
91: (x265,x266,x267) = 1;
92: (x268,x269,x270) = 1;
93: (x271,x272,x273) = 1;
94: (x274,x275,x276) = 1;
95: (x277,x278,x279) = 1;
96: (x280,x281,x282) = 1;
97: (x283,x284,x285) = 1;
98: (x286,x287,x288) = 1;
99: (x289,x290,x291) = 1;
100: (x292,x293,x294) = 1;
101: (x295,x296,x297) = 1;
102: (x298,x299,x300) = 1;
103: (x301,x302,x303) = 1;
104: (x304,x305,x306) = 1;
105: (x307,x308,x309) = 1;
106: (x310,x311,x312) = 1;
107: (x313,x314,x315) = 1;
108: (x316,x317,x318) = 1;
109: (x319,x320,x321) = 1;
110: (x322,x323,x324) = 1;
111: (x325,x326,x327) = 1;
112: (x328,x329,x330) = 1;
113: (x331,x332,x333) = 1;
114: (x334,x335,x336) = 1;
115: (x337,x338,x339) = 1;
116: (x340,x341,x342) = 1;
117: (x343,x344,x345) = 1;
118: (x346,x347,x348) = 1;
119: (x349,x350,x351) = 1;
120: (x352,x353,x354) = 1;
121: (x355,x356,x357) = 1;
122: (x358,x359,x360) = 1;
123: (x361,x362,x363) = 1;
124: (x364,x365,x366) = 1;
125: (x367,x368,x369) = 1;
126: (x370,x371,x372) = 1;
127: (x373,x374,x375) = 1;
128: (x376,x377,x378) = 1;
129: (x380,x381,x382) = 1;
130: (x383,x384,x385) = 1;
131: (x386,x387,x388) = 1;
132: (x389,x390,x391) = 1;
133: (x392,x393,x394) = 1;
134: (x395,x396,x397) = 1;
135: (x398,x399,x400) = 1;
136: (x401,x402,x403) = 1;
137: (x404,x405,x406) = 1;
138: (x407,x408,x409) = 1;
139: (x410,x411,x412) = 1;
140: (x413,x414,x415) = 1;
141: (x416,x417,x418) = 1;
142: (x419,x420,x421) = 1;
143: (x422,x423,x424) = 1;
144: (x425,x426,x427) = 1;
145: (x428,x429,x430) = 1;
146: (x431,x432,x433) = 1;
147: (x434,x435,x436) = 1;
148: (x437,x438,x439) = 1;
149: (x440,x441,x442) = 1;
150: (x443,x444,x445) = 1;
151: (x446,x447,x448) = 1;
152: (x449,x450,x451) = 1;
153: (x452,x453,x454) = 1;
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155: (x458,x459,x460) = 1;
156: (x461,x462,x463) = 1;
157: (x464,x465,x466) = 1;
158: (x467,x468,x469) = 1;
159: (x470,x471,x472) = 1;
160: (x473,x474,x475) = 1;
161: (x476,x477,x478) = 1;
162: (x479,x480,x481) = 1;
163: (x482,x483,x484) = 1;
164: (x485,x486,x487) = 1;
165: (x488,x489,x490) = 1;
166: (x491,x492,x493) = 1;
167: (x494,x495,x496) = 1;
168: (x497,x498,x499) = 1;
169: (x500,x501,x502) = 1;
170: (x503,x504,x505) = 1;
171: (x506,x507,x508) = 1;
172: (x509,x510,x511) = 1;
173: (x512,x513,x514) = 1;
174: (x515,x516,x517) = 1;
175: (x518,x519,x520) = 1;
176: (x521,x522,x523) = 1;
177: (x524,x525,x526) = 1;
178: (x527,x528,x529) = 1;
179: (x530,x531,x532) = 1;
180: (x533,x534,x535) = 1;
181: (x536,x537,x538) = 1;
182: (x539,x540,x541) = 1;
183: (x542,x543,x544) = 1;
184: (x545,x546,x547) = 1;
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186: (x551,x552,x553) = 1;
187: (x554,x555,x556) = 1;
188: (x557,x558,x559) = 1;
189: (x560,x561,x562) = 1;
190: (x563,x564,x565) = 1;
191: (x566,x567,x568) = 1;
192: (x569,x570,x571) = 1;
193: (x572,x573,x574) = 1;
194: (x575,x576,x577) = 1;
195: (x578,x579,x580) = 1;
196: (x581,x582,x583) = 1;
197: (x584,x585,x586) = 1;
198: (x587,x588,x589) = 1;
199: (x590,x591,x592) = 1;
200: (x593,x594,x595) = 1;
201: (x596,x597,x598) = 1;
202: (x599,x600,x601) = 1;
203: (x602,x603,x604) = 1;
204: (x605,x606,x607) = 1;
205: (x608,x609,x610) = 1;
206: (x611,x612,x613) = 1;
207: (x614,x615,x616) = 1;
208: (x617,x618,x619) = 1;
209: (x620,x621,x622) = 1;
210: (x623,x624,x625) = 1;
211: (x626,x627,x628) = 1;
212: (x629,x630,x631) = 1;
213: (x632,x633,x634) = 1;
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215: (x638,x639,x640) = 1;
216: (x641,x642,x643) = 1;
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222: (x659,x660,x661) = 1;
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224: (x665,x666,x667) = 1;
225: (x668,x669,x670) = 1;
226: (x671,x672,x673) = 1;
227: (x674,x675,x676) = 1;
228: (x677,x678,x679) = 1;
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231: (x686,x687,x688) = 1;
232: (x689,x690,x691) = 1;
233: (x692,x693,x694) = 1;
234: (x695,x696,x697) = 1;
235: (x698,x699,x700) = 1;
236: (x701,x702,x703) = 1;
237: (x704,x705,x706) = 1;
238: (x707,x708,x709) = 1;
239: (x710,x711,x712) = 1;
240: (x713,x714,x715) = 1;
241: (x716,x717,x718) = 1;
242: (x719,x720,x721) = 1;
243: (x722,x723,x724) = 1;
244: (x725,x726,x727) = 1;
245: (x728,x729,x730) = 1;
246: (x731,x732,x733) = 1;
247: (x734,x735,x736) = 1;
248: (x737,x738,x739) = 1;
249: (x740,x741,x742) = 1;
250: (x743,x744,x745) = 1;
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252: (x749,x750,x751) = 1;
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254: (x755,x756,x757) = 1;
255: (x758,x759,x760) = 1;
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257: (x764,x765,x766) = 1;
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262: (x779,x780,x781) = 1;
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266: (x791,x792,x793) = 1;
267: (x794,x795,x796) = 1;
268: (x797,x798,x799) = 1;
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270: (x803,x804,x805) = 1;
271: (x806,x807,x808) = 1;
272: (x809,x810,x811) = 1;
273: (x812,x813,x814) = 1;
274: (x815,x816,x817) = 1;
275: (x818,x819,x820) = 1;
276: (x821,x822,x823) = 1;
277: (x824,x825,x826) = 1;
278: (x827,x828,x829) = 1;
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283: (x842,x843,x844) = 1;
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286: (x851,x852,x853) = 1;
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292: (x869,x870,x871) = 1;
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296: (x881,x882,x883) = 1;
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305: (x908,x909,x910) = 1;
306: (x911,x912,x913) = 1;
307: (x914,x915,x916) = 1;
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309: (x920,x921,x922) = 1;
310: (x923,x924,x925) = 1;
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312: (x929,x930,x931) = 1;
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314: (x935,x936,x937) = 1;
315: (x938,x939,x940) = 1;
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326: (x971,x972,x973) = 1;
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328: (x977,x978,x979) = 1;
329: (x980,x981,x982) = 1;
330: (x983,x984,x985) = 1;
331: (x986,x987,x988) = 1;
332: (x989,x990,x991) = 1;
333: (x992,x993,x994) = 1;
334: (x995,x996,x997) = 1;
335: (x998,x999,x1000) = 1;

```

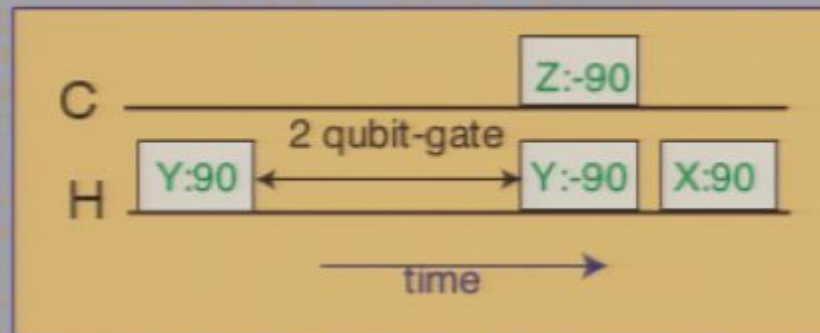


Quantum algorithms 101: the Control-NOT

Control-Not
Target



Quantum circuit

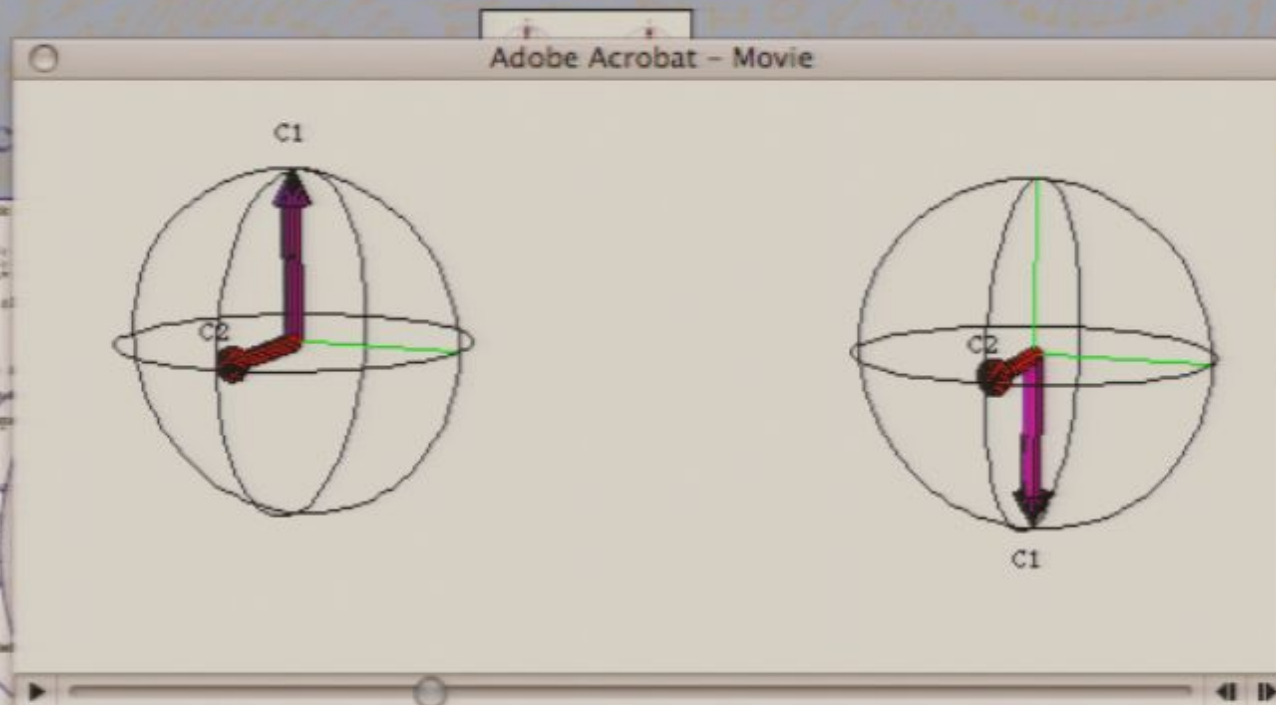


Pre-c

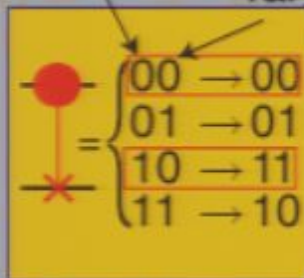
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1) setting to trade
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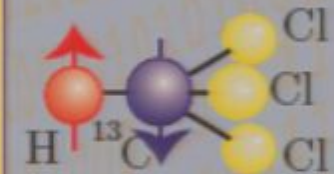
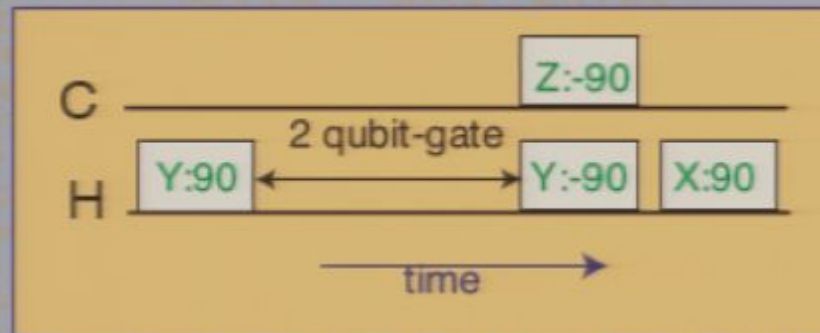
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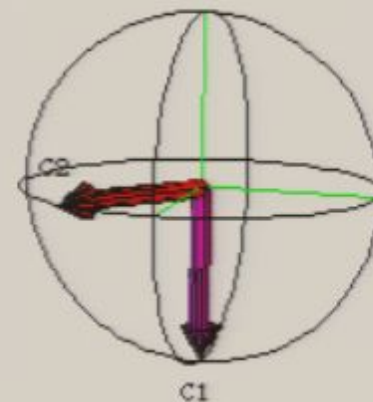
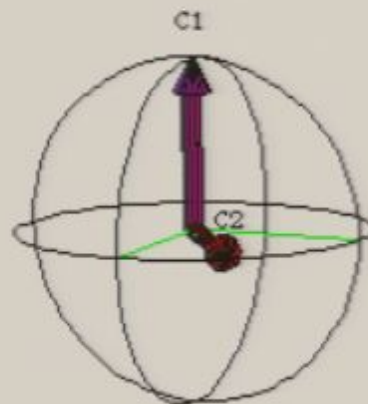
Control-Not Target

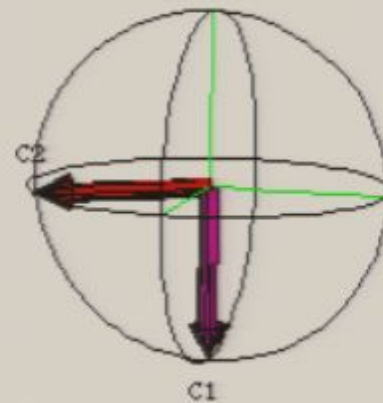
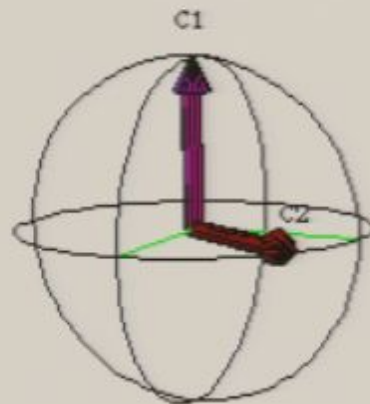
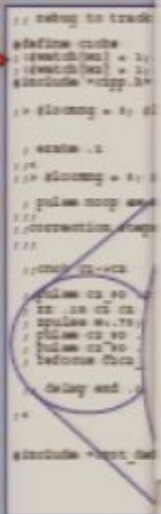
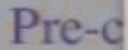
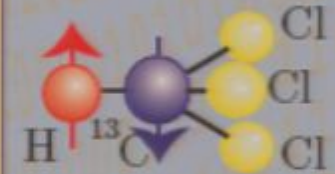
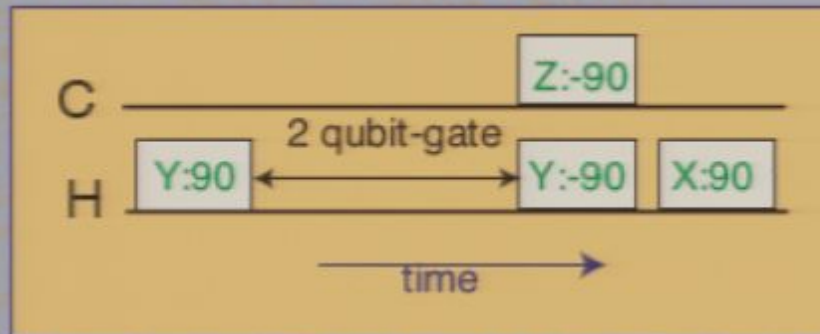
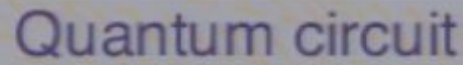
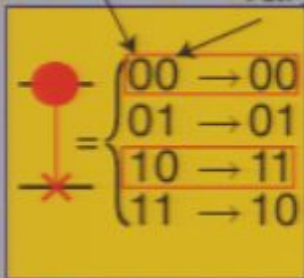
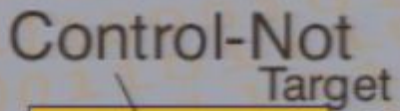


Quantum circuit

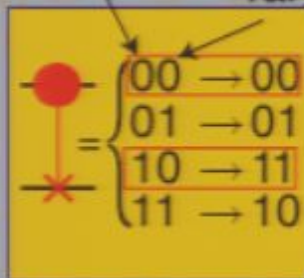


Adobe Acrobat – Movie

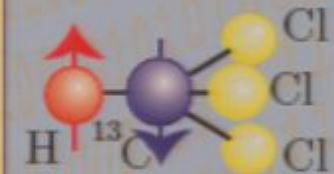
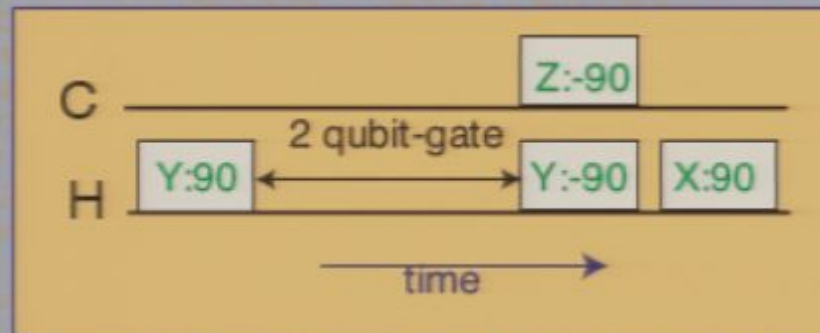




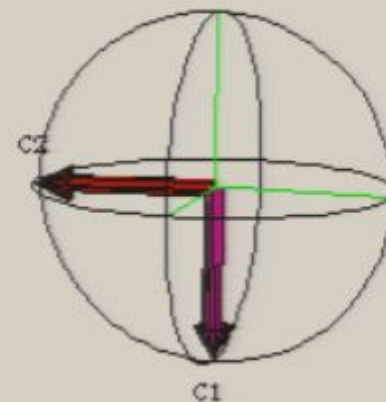
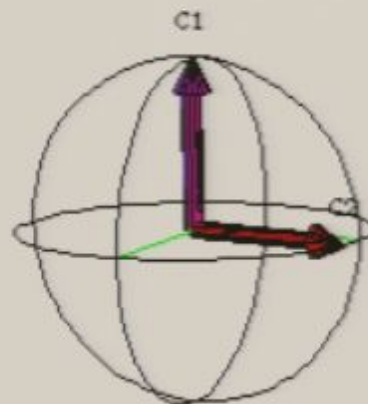
Control-Not
Target



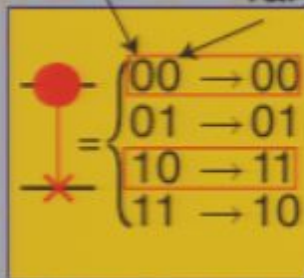
Quantum circuit



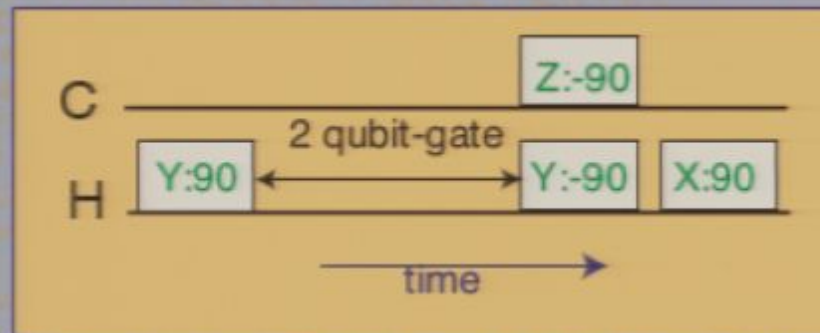
Adobe Acrobat – Movie



Control-Not Target

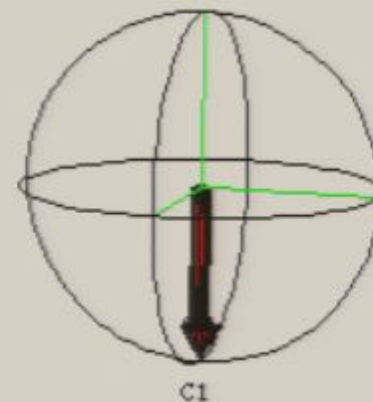
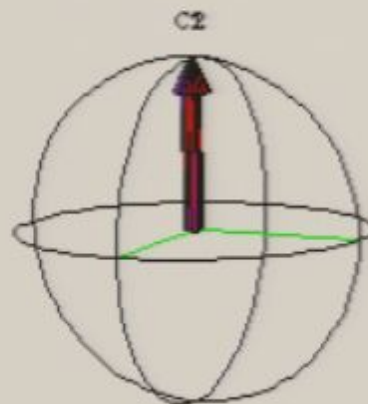


Quantum circuit



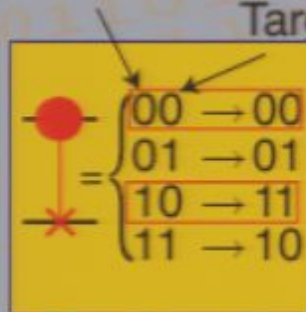
Adobe Acrobat – Movie

Pre-c

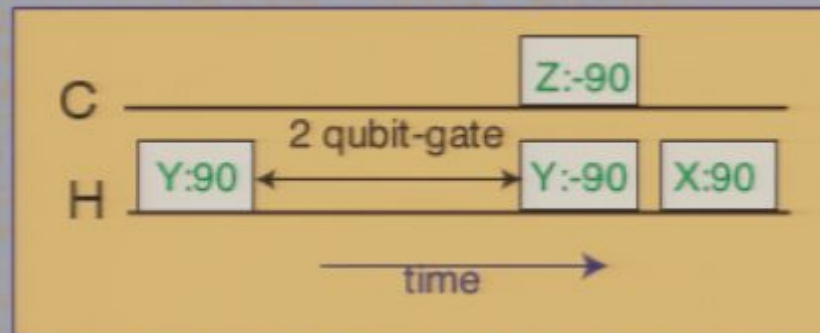


Quantum algorithms 101: the Control-NOT

Control-Not



Quantum circuit



Pre-compiler (Optimizer)

```

// setup to track down error sources by doing partial error correction.
define cube
{
  switch(m) = 1;
  switch(m) = 1;
  include "cub.h"
}
// slowing = 1; slowing = 2; 4;
// scale = 1
// slowing = 1; slowing
// pulse loop and v
// correction stage
//
// C1 C2
// pulse C1 90
// zz .25 C1 C2
// zpulse C1:.75;C2:
// pulse C2_90 .75
// pulse C2_90 .0
// refocus C1C2_180

```

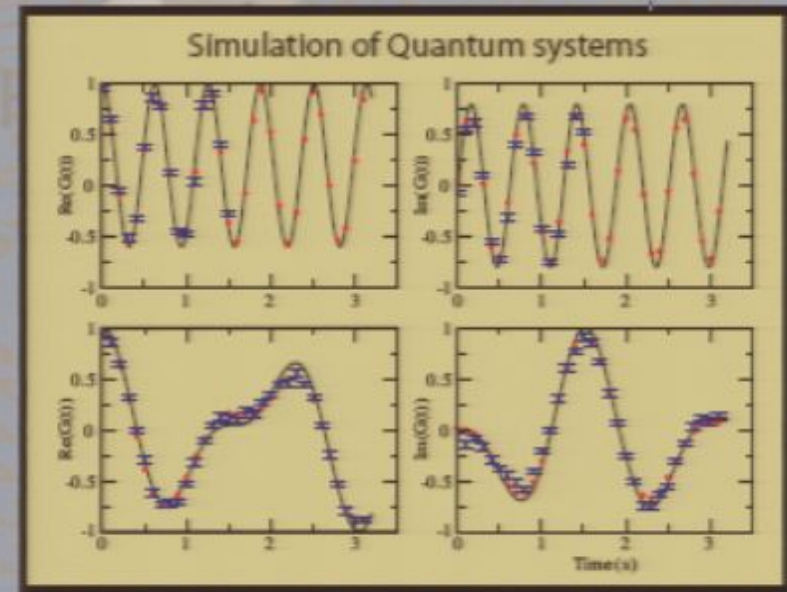
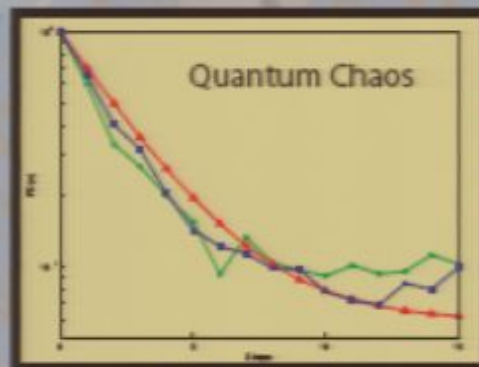
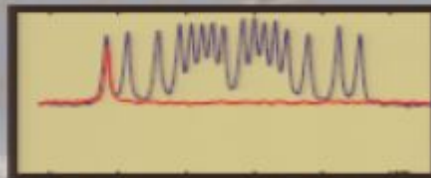
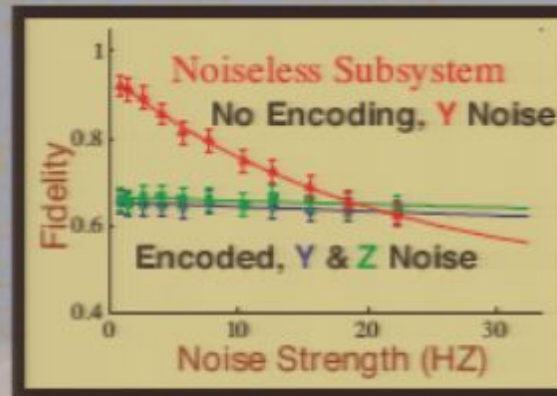
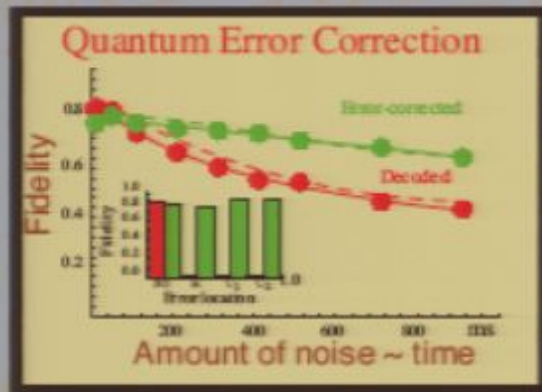
Brucker (machine) language

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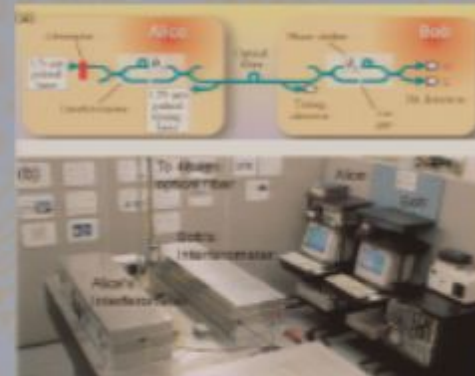
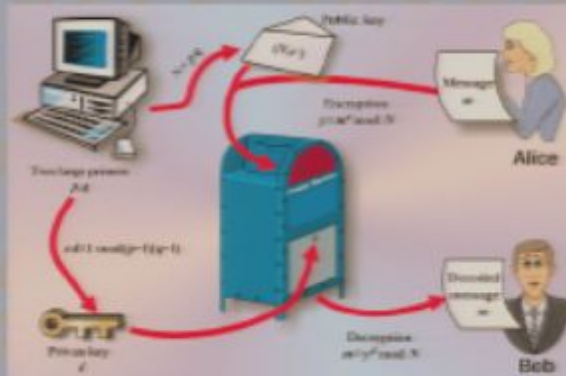
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Expt. on small QIP:

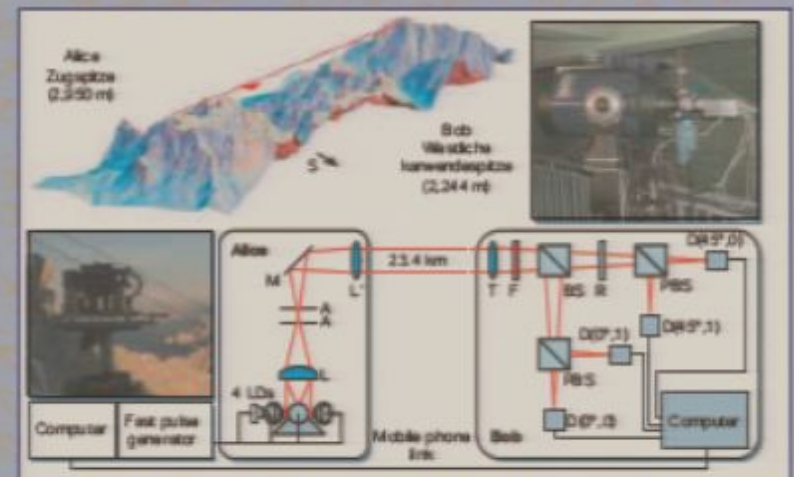


Quantum cryptography

Idea: using the inevitable disturbance in the measurement process of quantum mechanical systems as a tool to monitor eavesdropping:



Quantum Cryptography in the world:
 NSA and Los Alamos National Laboratory
www.losalamos.gov
 Rarity's group
www.dera.gov.uk
 The Norwegian group www.vad1.com/qcr
 BBN Technologies:
www.bbn.com/networking/quantumcryptography.html
 IDQuantique:
www.idquantique.com/
 MagiQ:



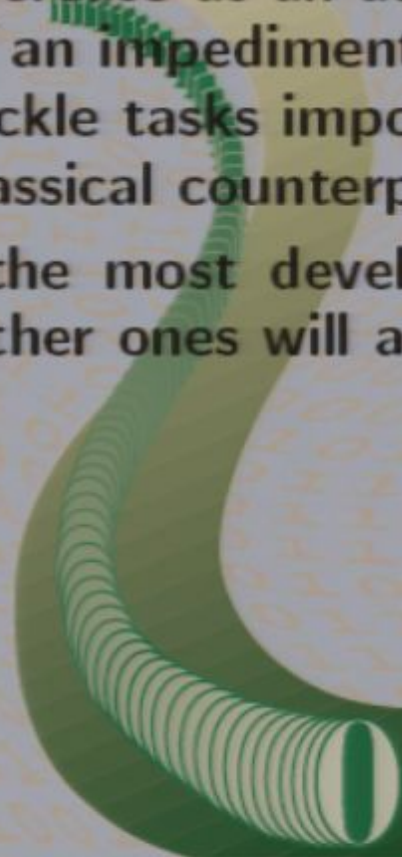
Controlling forces of nature:



Conclusion



- Many of today's technologies are going towards the quantum scale.
- Quantum information take this decrease as an advantage instead of an impediment, it allows to tackle tasks impossible for its classical counterpart.
- Quantum information is the most developed of the potential quantum technologies but other ones will also be created.



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Institute for
Quantum
Computing

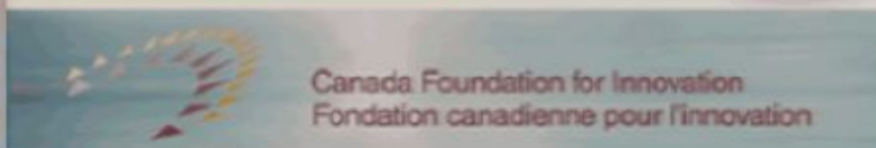


The
National
Security
Agency

ARDA



ONTARIO
CHALLENGE FUND
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Chairs

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microsystems

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No Signal

VGA-1

No Signal

VGA-1

No Signal

VGA-1

