

Title: Harnessing the Quantum World

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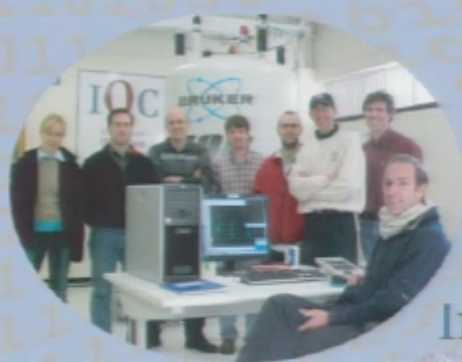
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Abstract: Are you ready for this upgrade? The very foundation of computer science is changing. As Moore's Law draws to a close, rules of quantum physics are taking over. Learn how leading researchers are using counterintuitive effects, such as superposition, in their quest to build ultra-powerful quantum computers. You'll see how quantum particles behave, are controlled and, ultimately, used to calculate. <kw>quantum world, Raymond Laflamme, quantum mechanics, quantum information, quantum computing, information processing, Moore's Law, quantum scale, complexity theory, cryptography, qubits, quantum bits, quantum states, nuclear magnetic resonance, Turing </kw>

Harnessing the Quantum World



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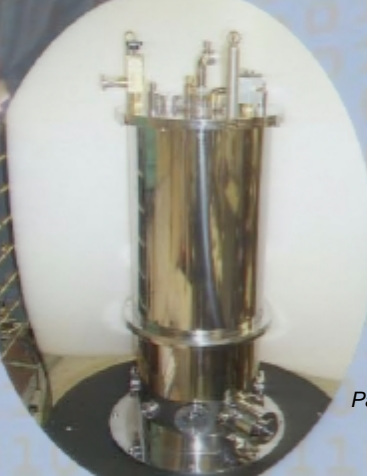
IQC



Institute for **Quantum** Computing



Raymond Laflamme
laflamme@iqc.ca



Harnessing the Quantum World

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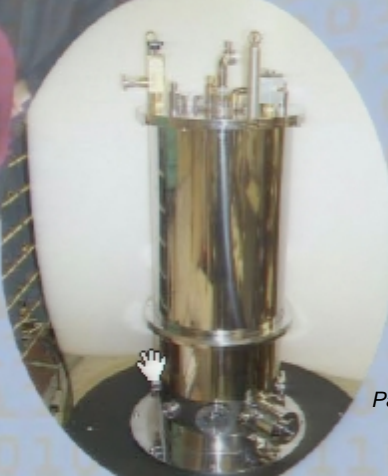
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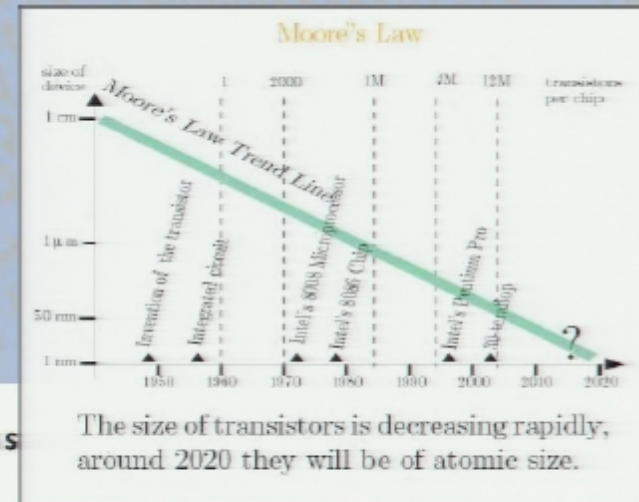
- Why quantum information?
- What is quantum computing?
- Steps towards building these devices.

Information Processing Devices



Why Quant. Info. Processing?

We are advancing towards the quantum scale!



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SCIENCE'S COMPASS

PERSPECTIVES: DEVICE PHYSICS

Pushing the Limits

Paul A. Packan

For the past 30 years, the semiconductor industry has followed Moore's law, which states that transistor performance and density double every 3 years (1). Although not truly a law, Gordon Moore's statement has yet to be violated. But now it seems to be in serious danger. Fundamental thermodynamic 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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These fundamental issues have not previously limited the scaling of transistors and represent a considerable challenge for the semiconductor industry. There are currently no known solutions to these problems. To continue the performance trends of the past 20 years and maintain Moore's law of improvement will be the most difficult challenge the semiconductor industry has ever faced.

References

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

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

Enterprise hardware

Intel scientists find wall for Moore's Law

Last modified: December 1, 2000, 4:00 AM PST

By Michael Kanellos
Staff Writer, CNET News.com

PRINT EMAIL SHARE

Moore's Law, as chip manufacturers generally refer to it today, is coming to an end, according to a recent research paper.

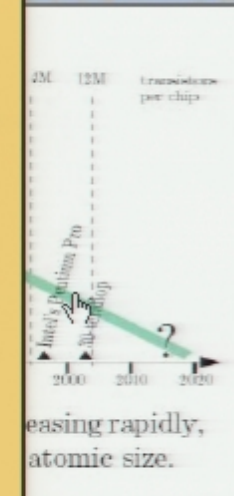
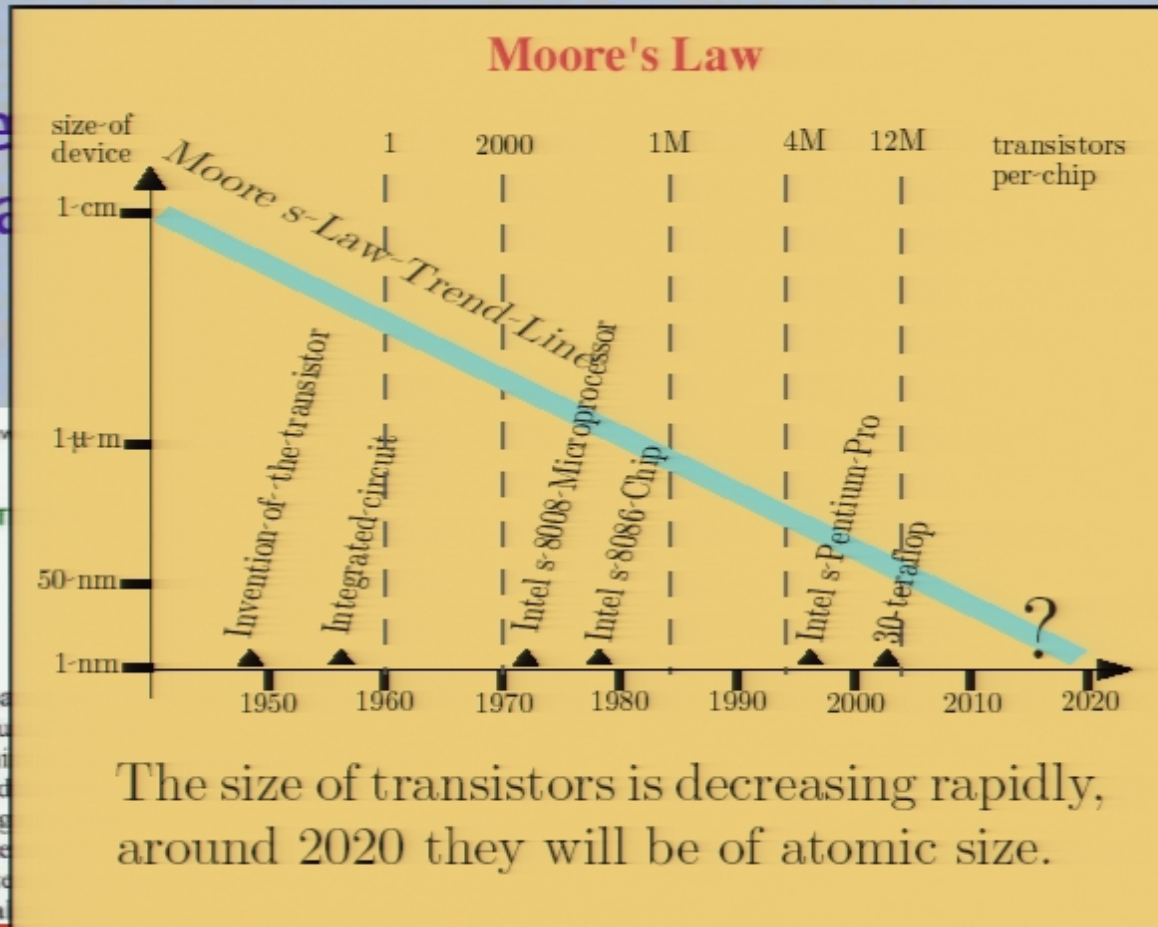
Granted, that end likely won't come for about two decades, but Intel researchers have recently published a paper theorizing that chipmakers will hit a wall when it comes to shrinking the size of transistors, one of the chief methods for making chips that are smaller, more powerful and cheaper than their predecessors.

Manufacturers 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.

The author is at Intel Corporation, 5200 NE Elam Parkway, Hillsboro, OR 97124, USA. E-mail: paula.packan@intel.com

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PERSPECTIVE

For the past few decades, the transistor industry has followed Moore's law, which states that the performance and cost of integrated circuits (ICs) will double every two years. Although Moore's law has been a guiding principle for the semiconductor industry, it is now being challenged. But now it seems that the fundamental limit of Moore's law is being reached in critical areas, and unless new, innovative solutions are found, the current rate of improvement cannot be maintained.

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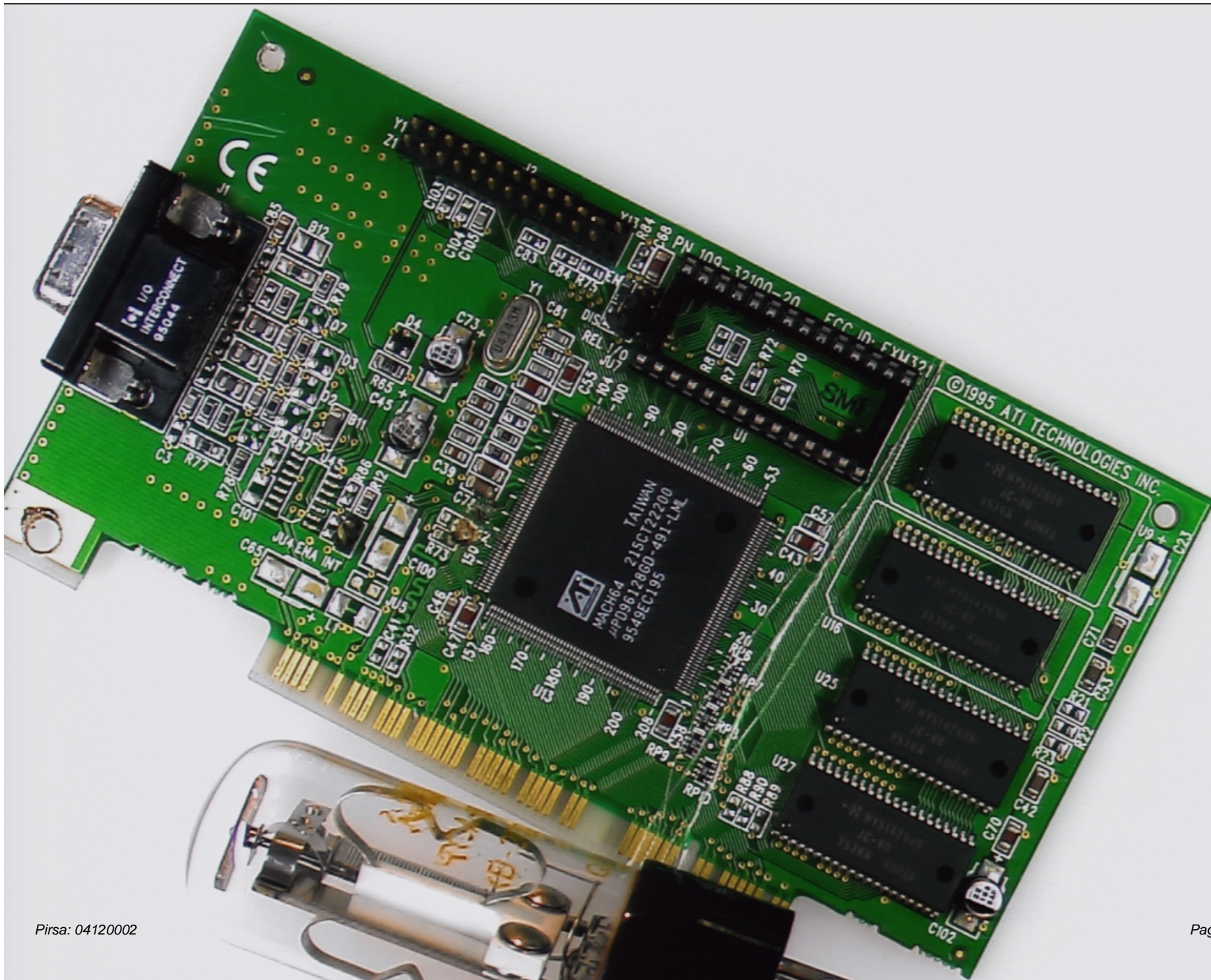
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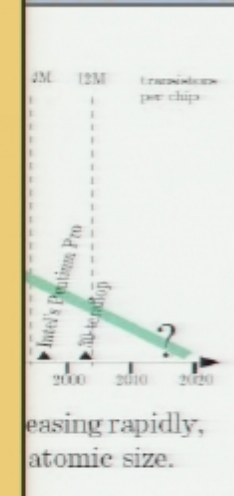
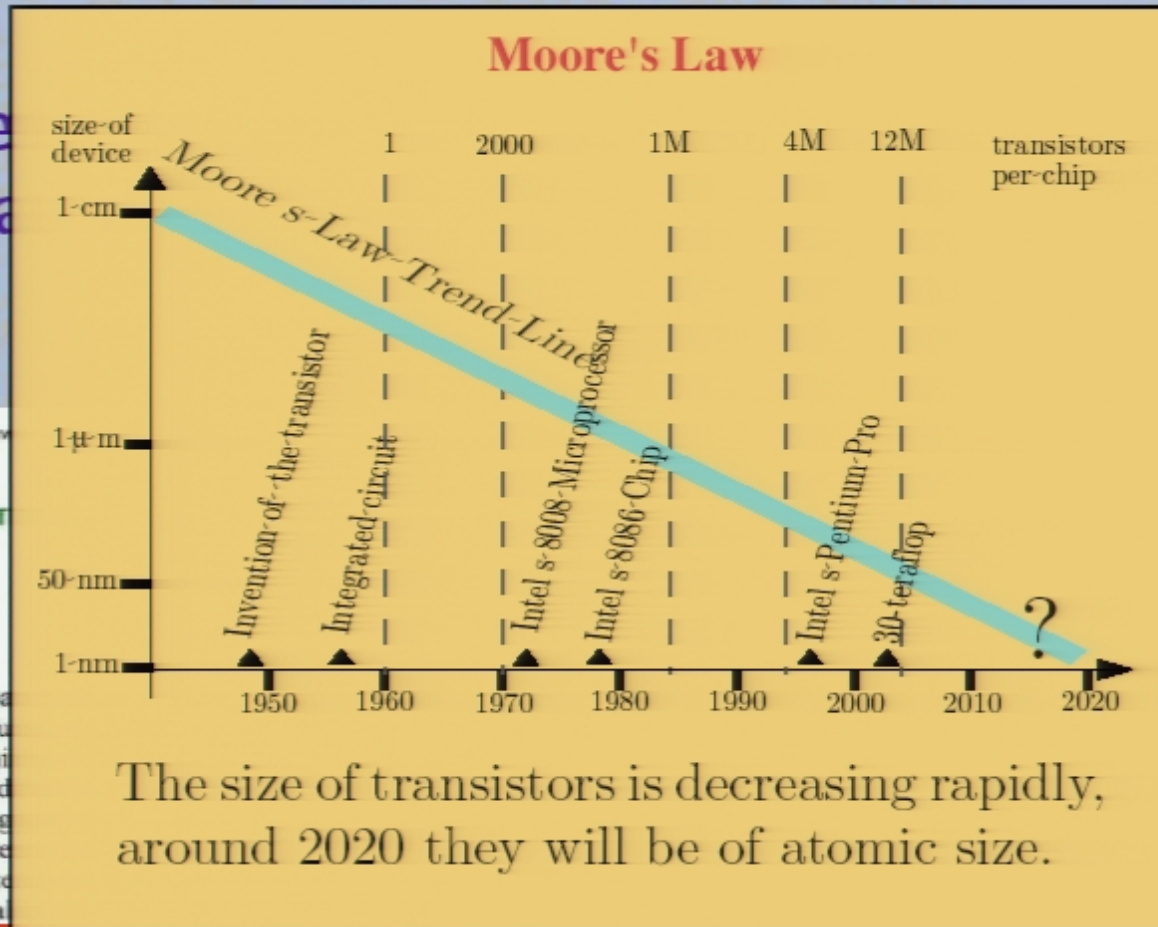
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Why Quant. Info. Processing?

Where the technology is going...

Quantum mechanics was discovered 100 years ago:

- for more than the first half a century we struggled to understand its implications at describing the world around us: quantum mechanics is seen as an obstacle
- there has been technology using some feature of quantum mechanics: the transistor, the laser, MRI
- Moore's law suggests that we need to control quantum systems
- around 1980 things have started to change...

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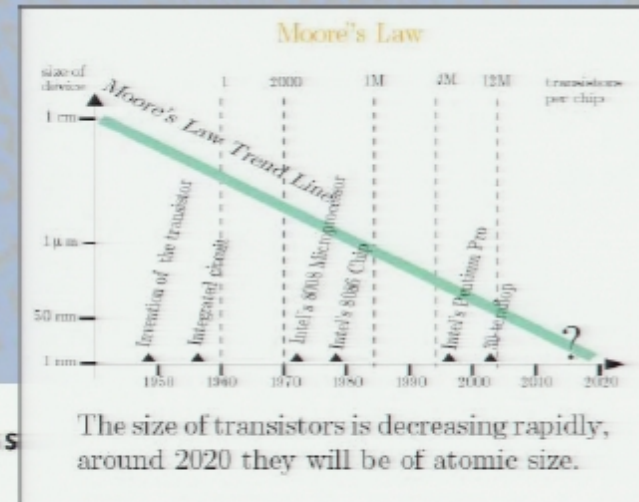
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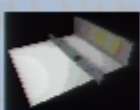
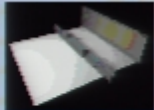
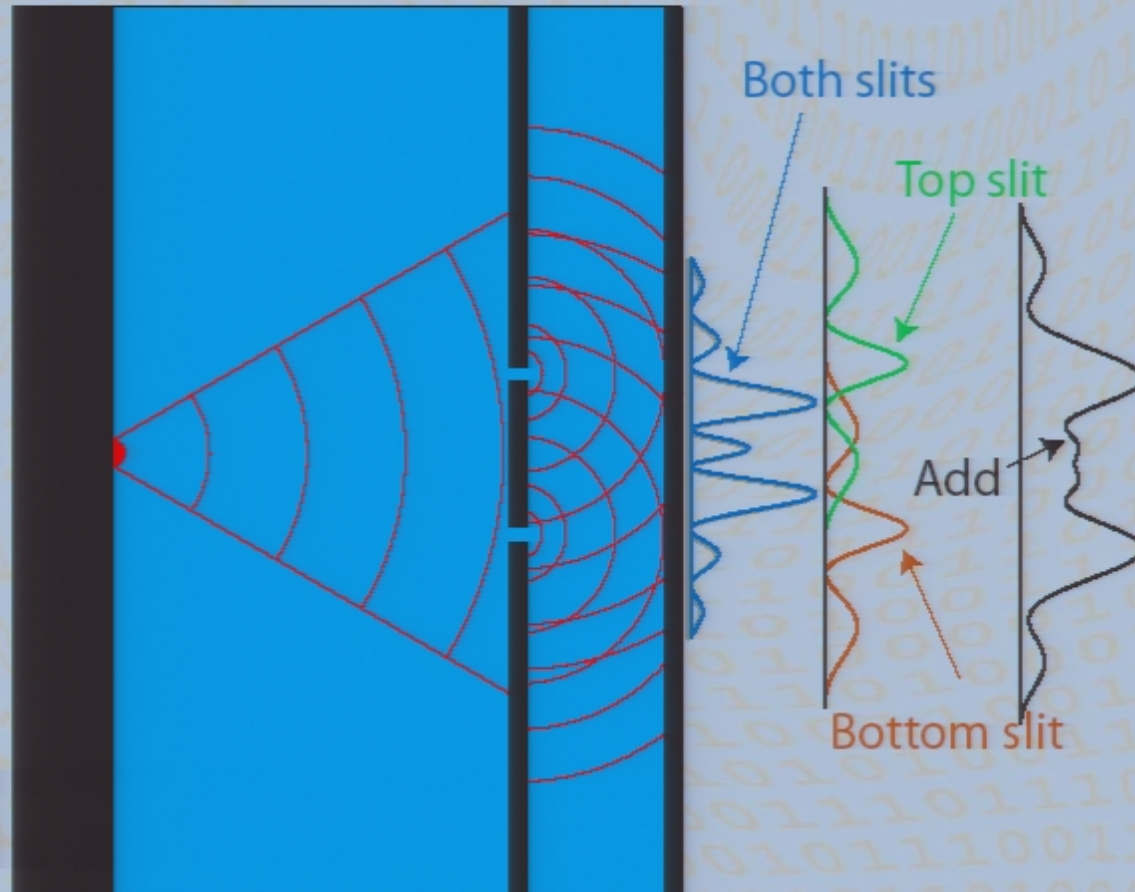
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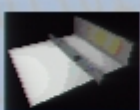
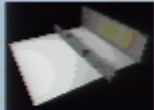
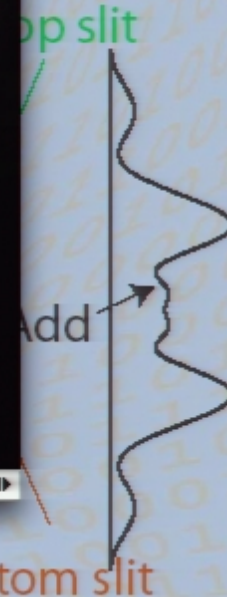
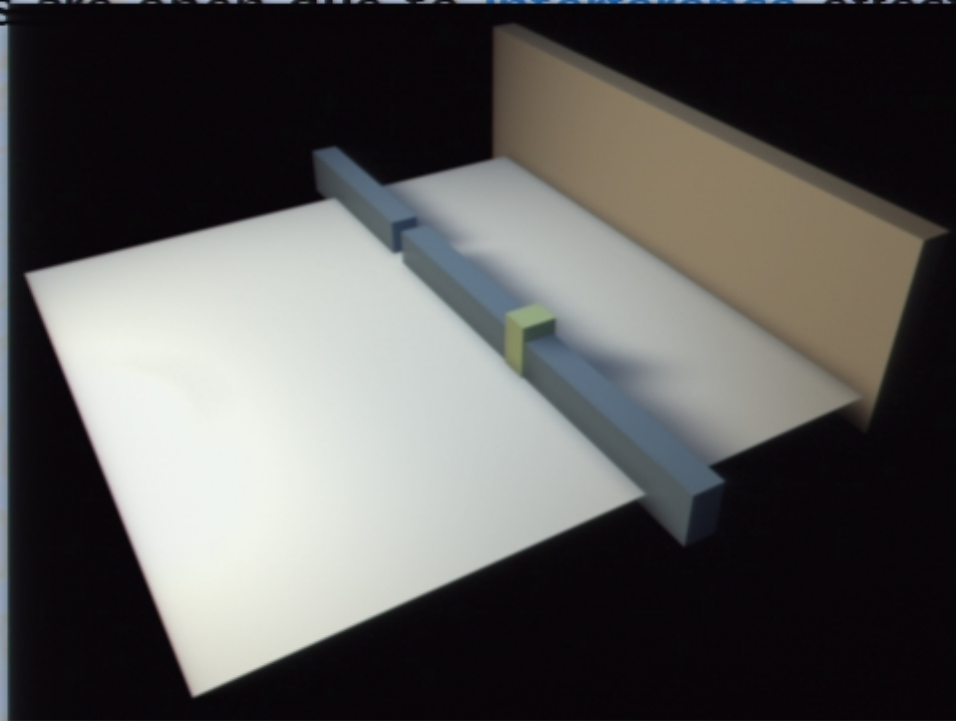
Basics of Quantum Mechanics

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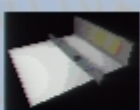
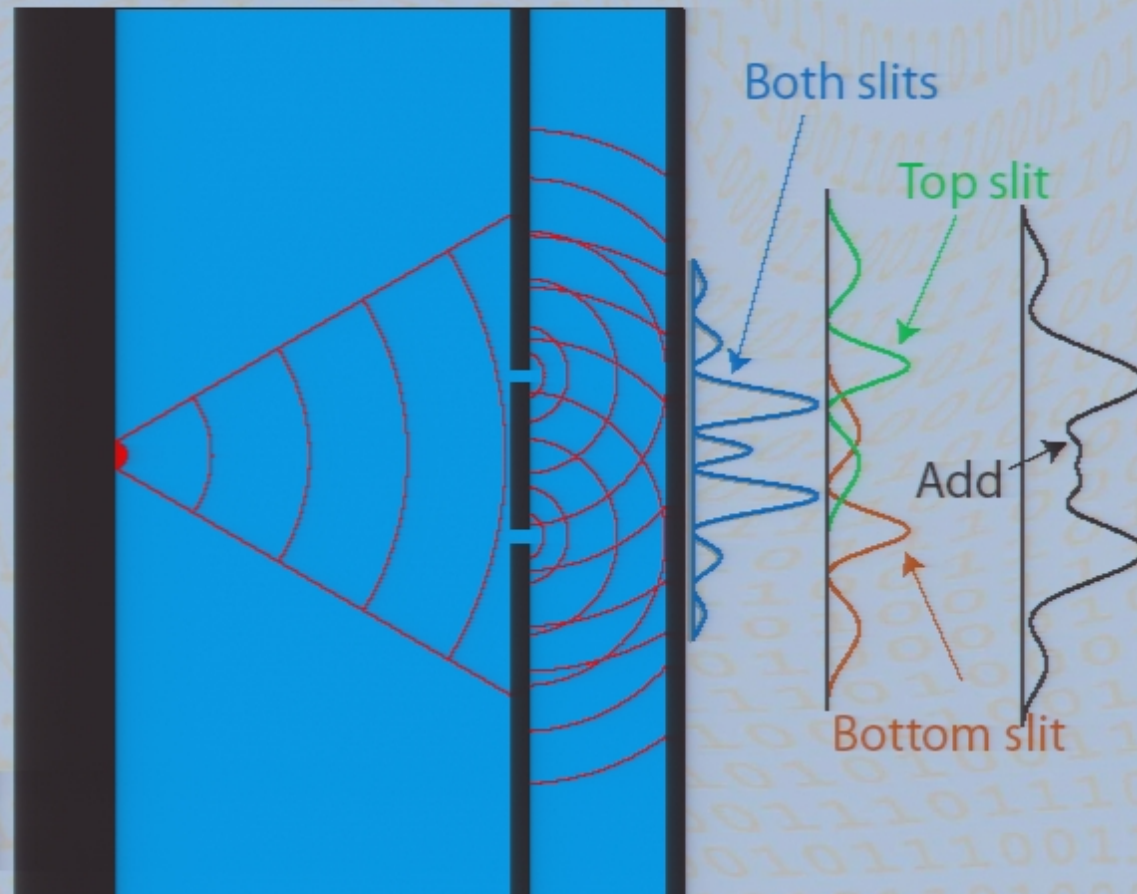
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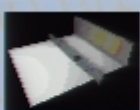
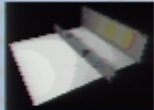
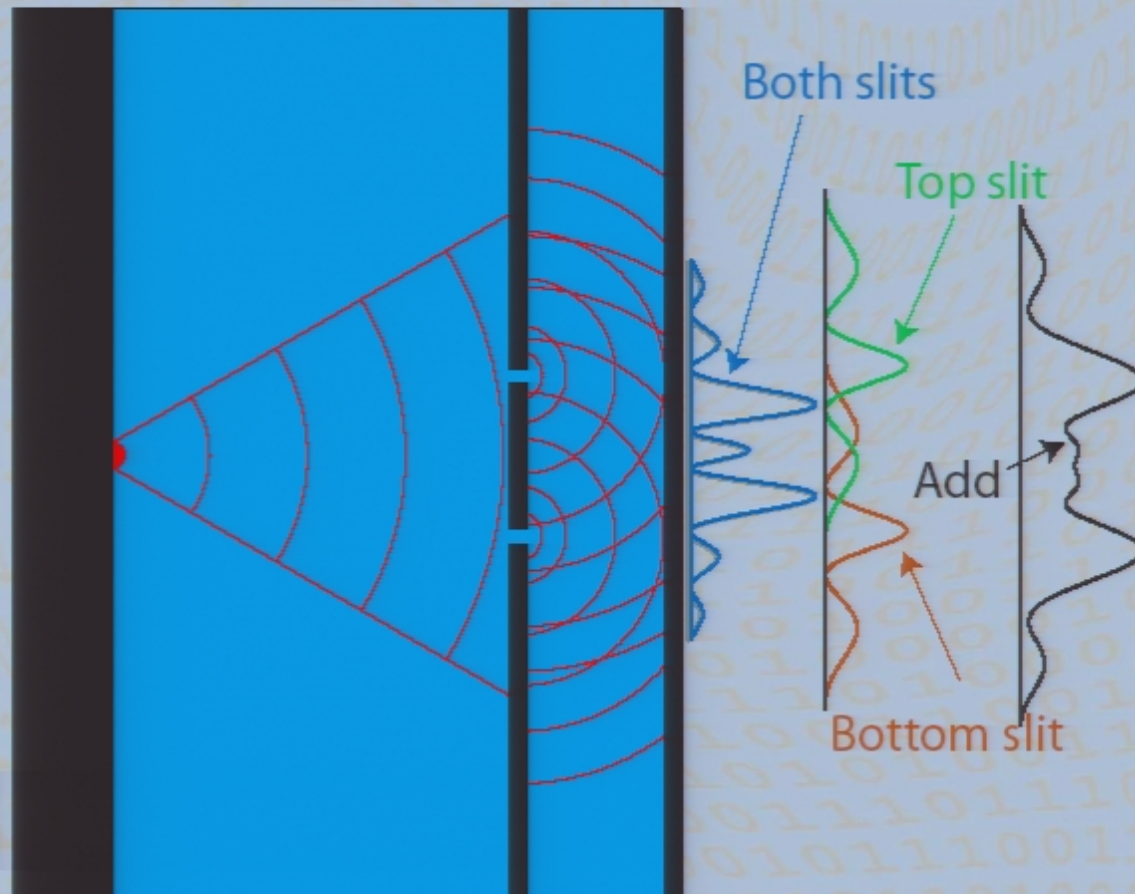
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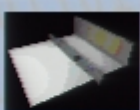
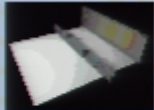
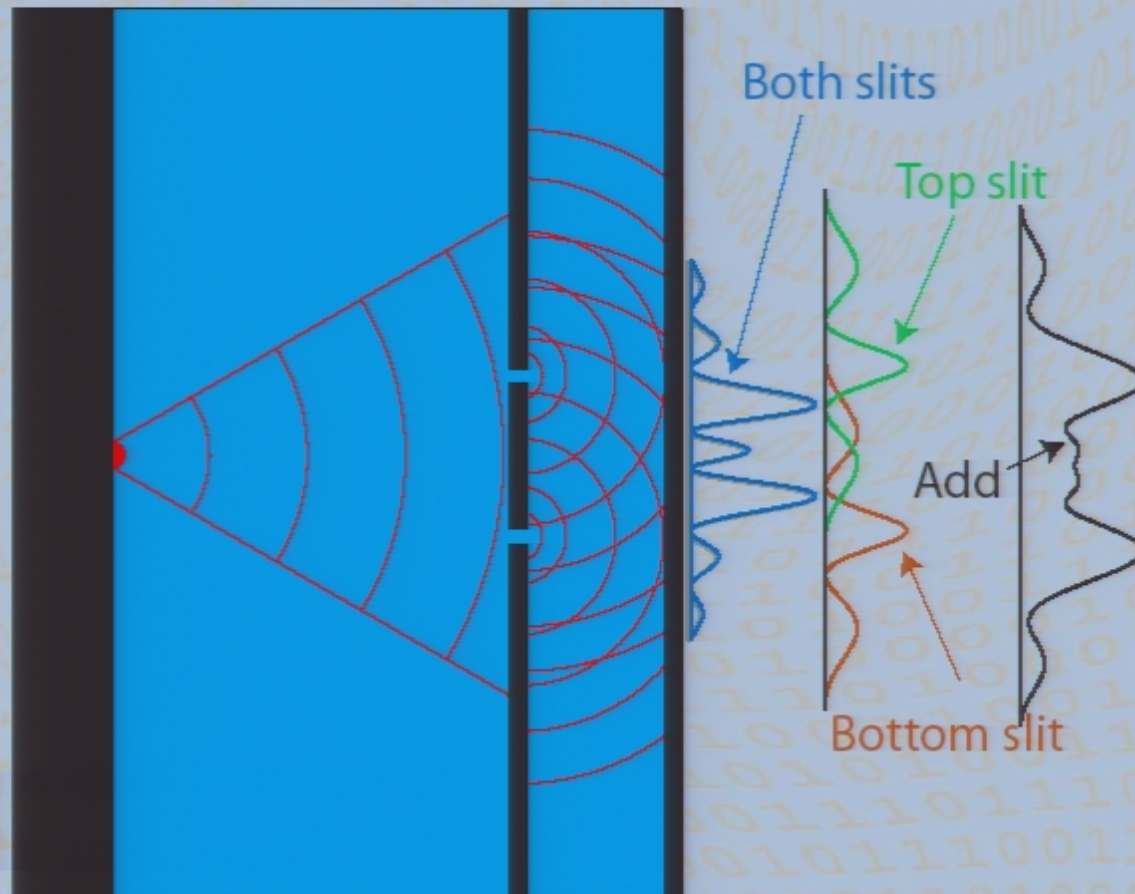
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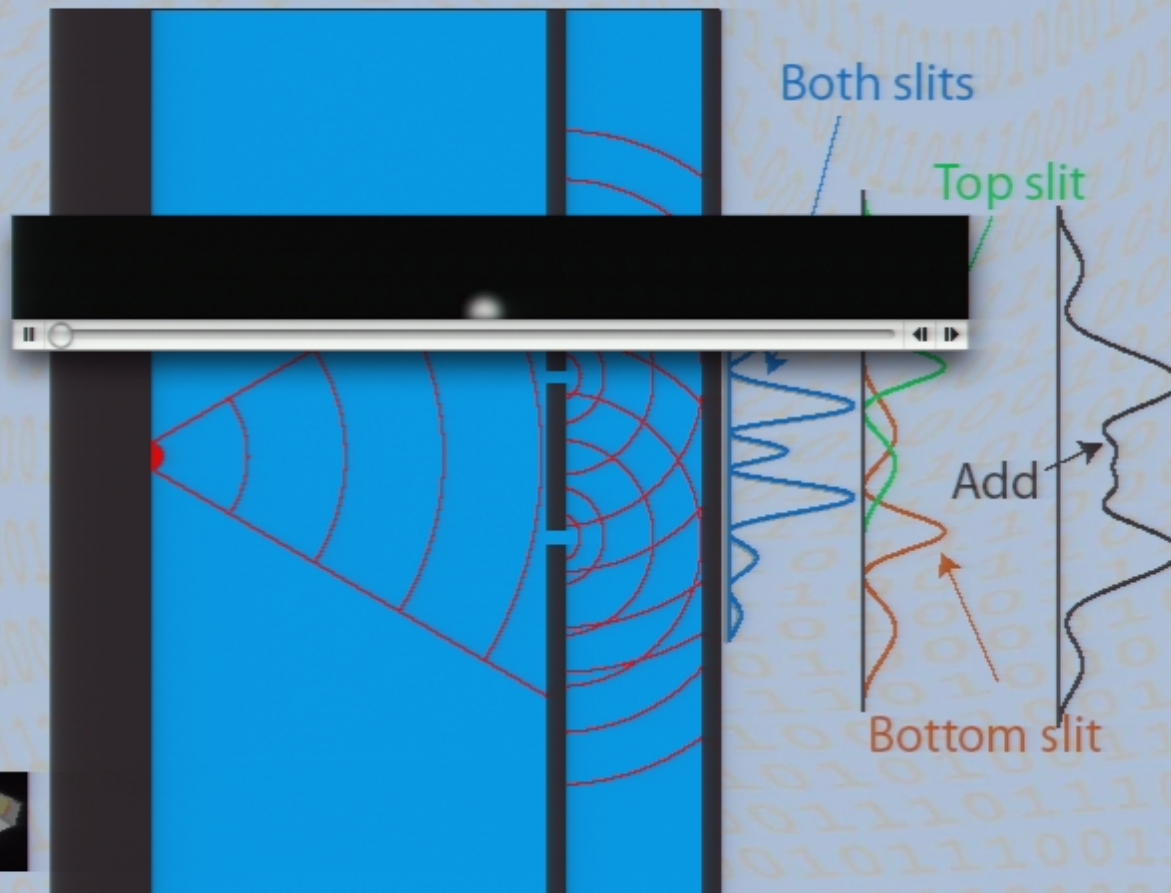
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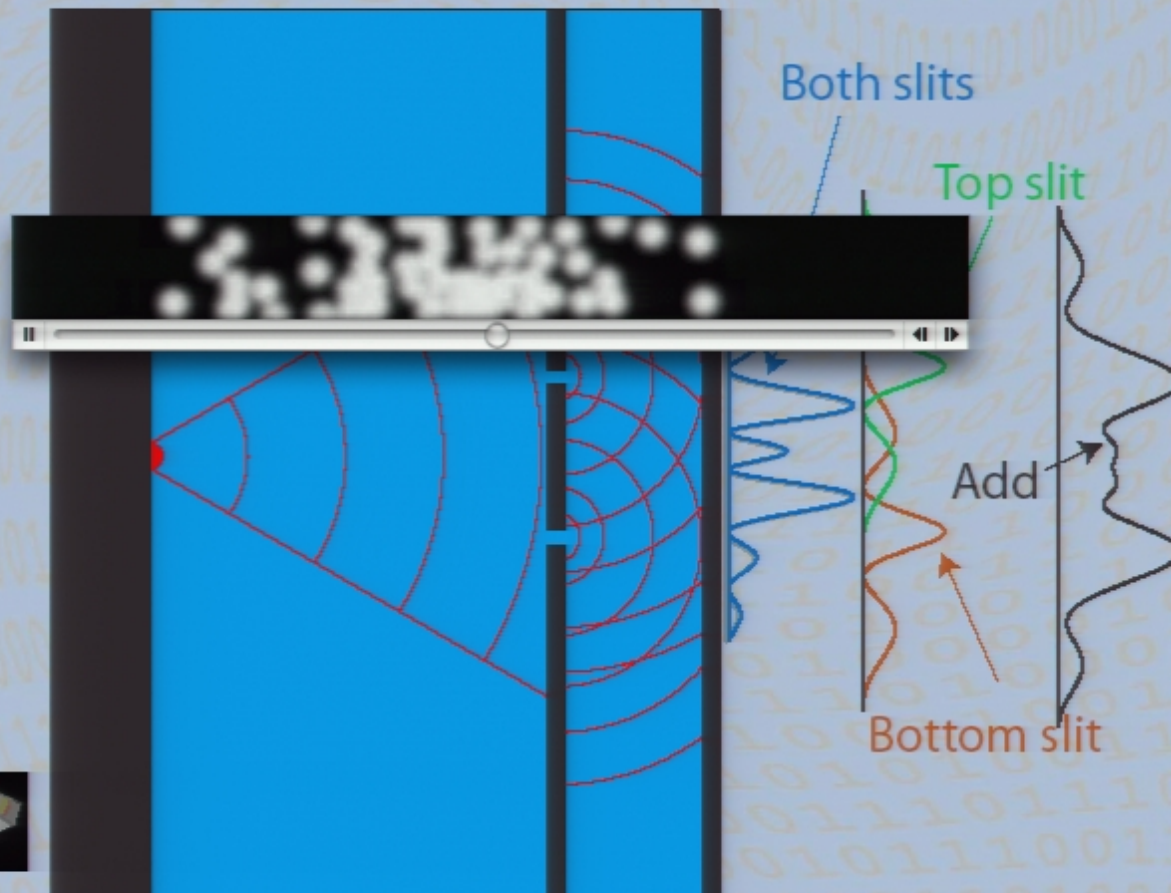
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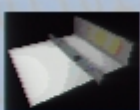
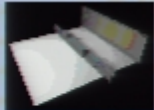
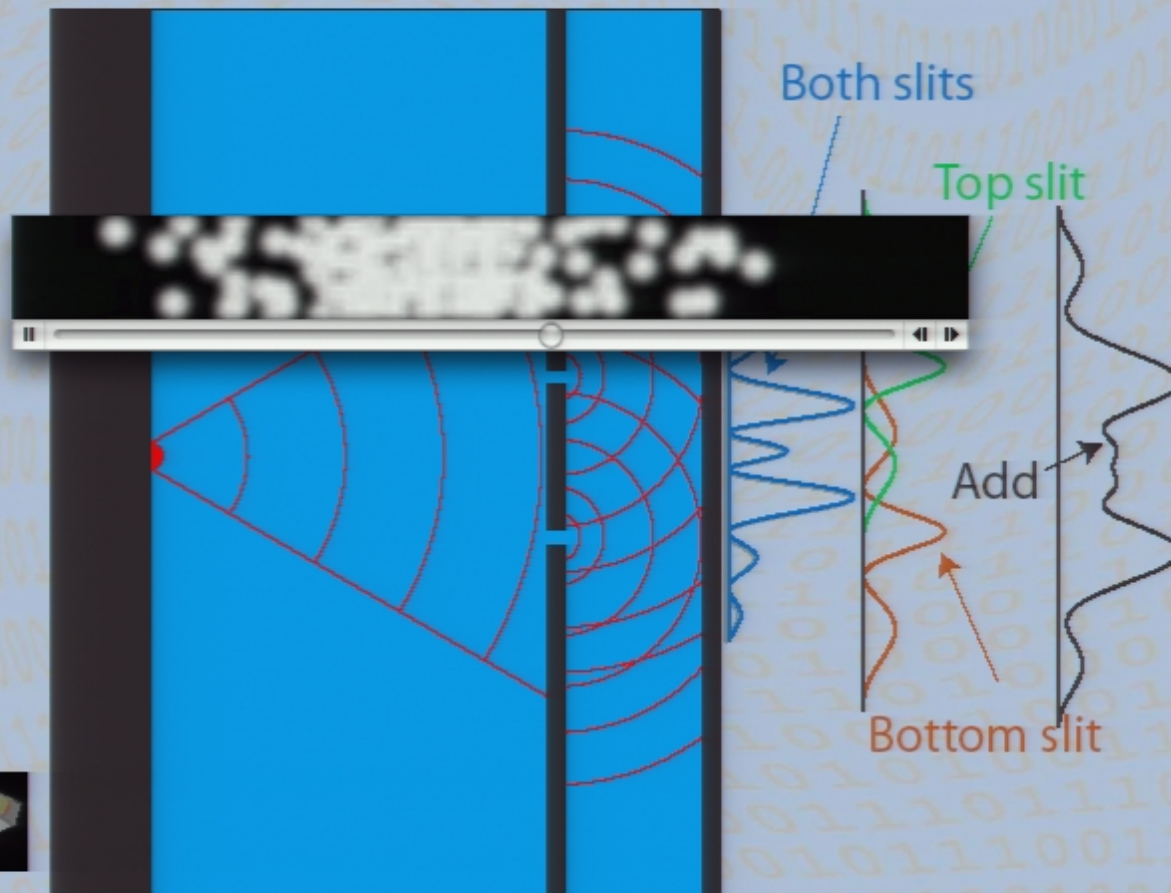
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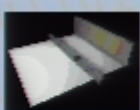
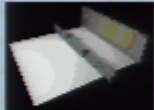
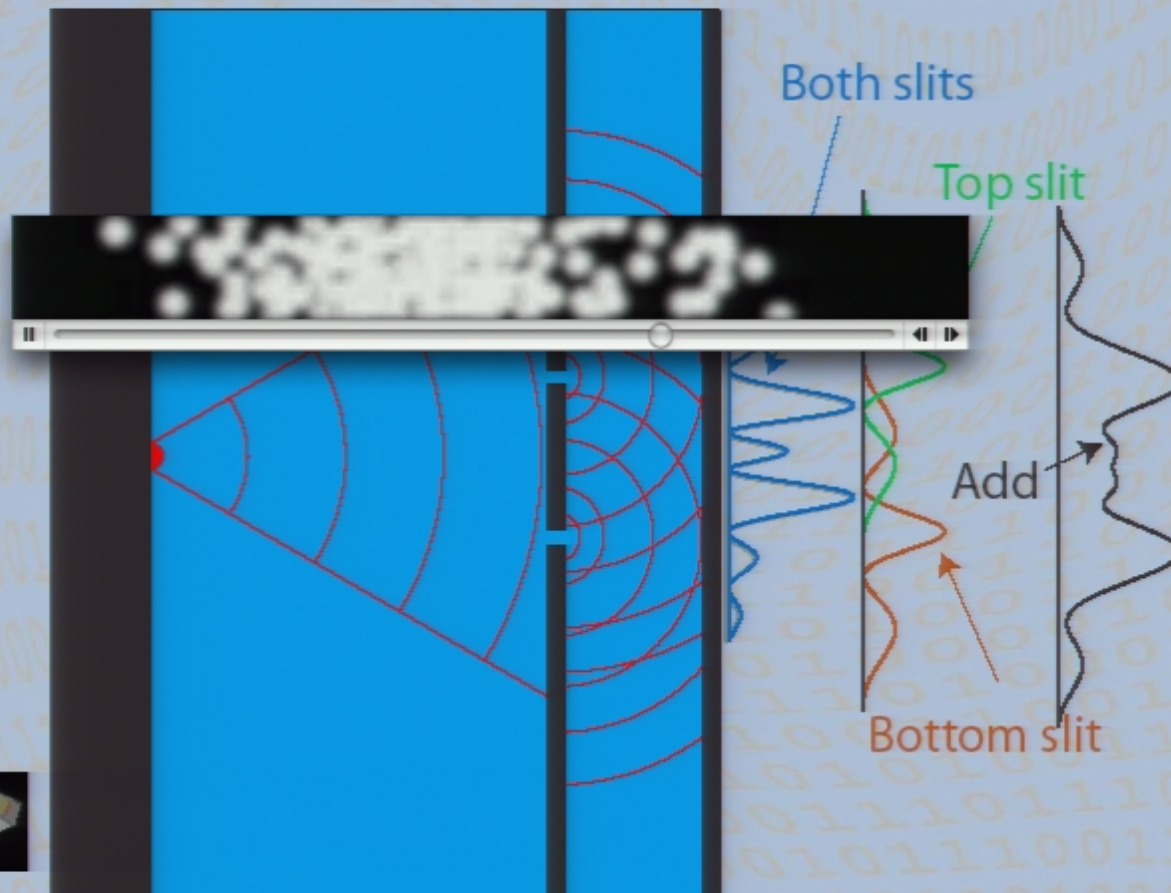
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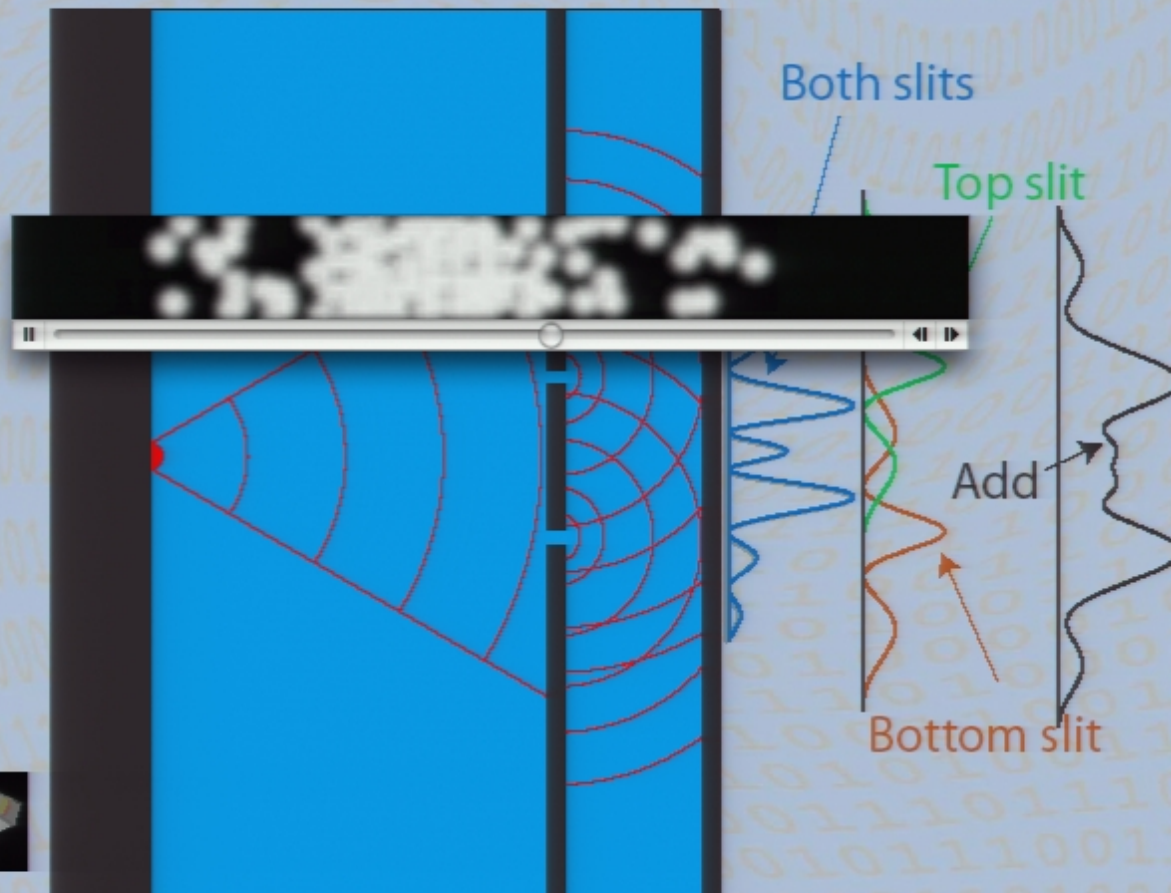
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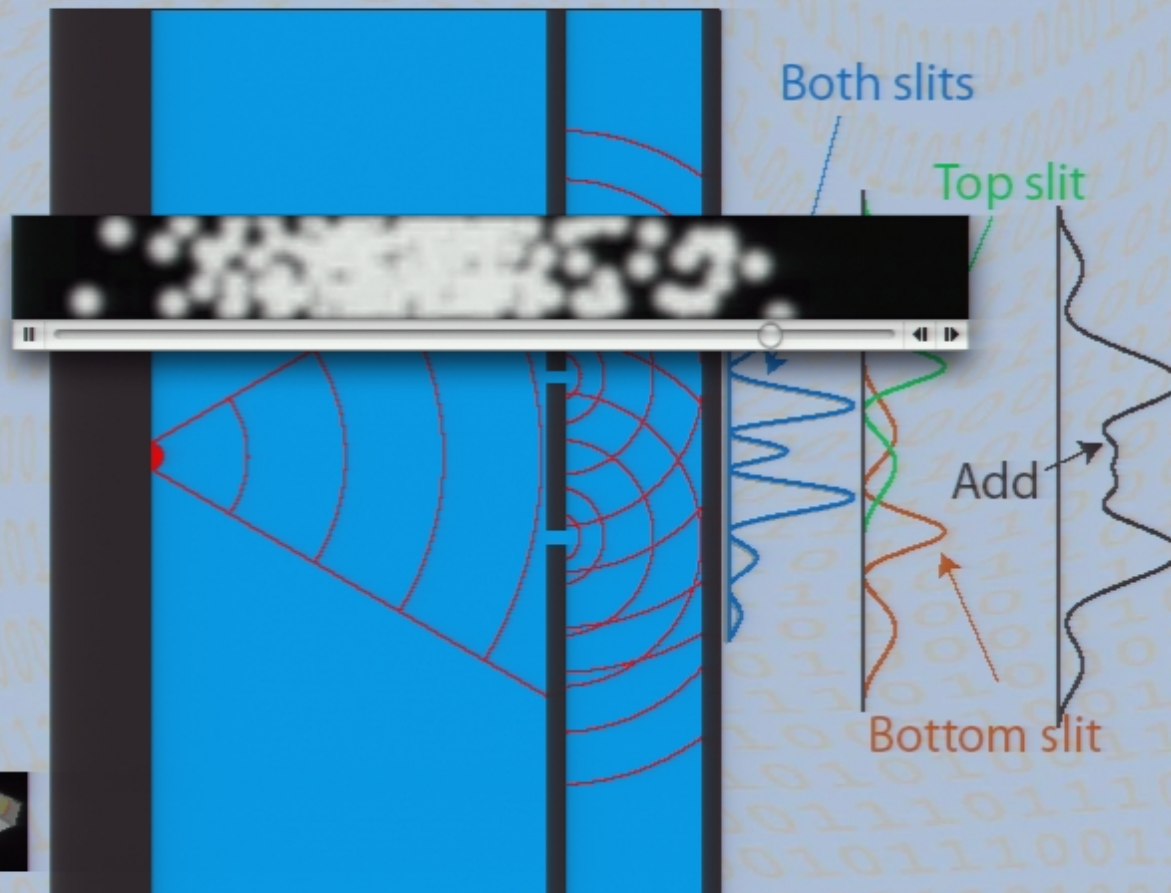
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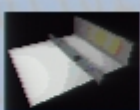
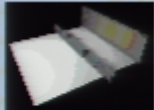
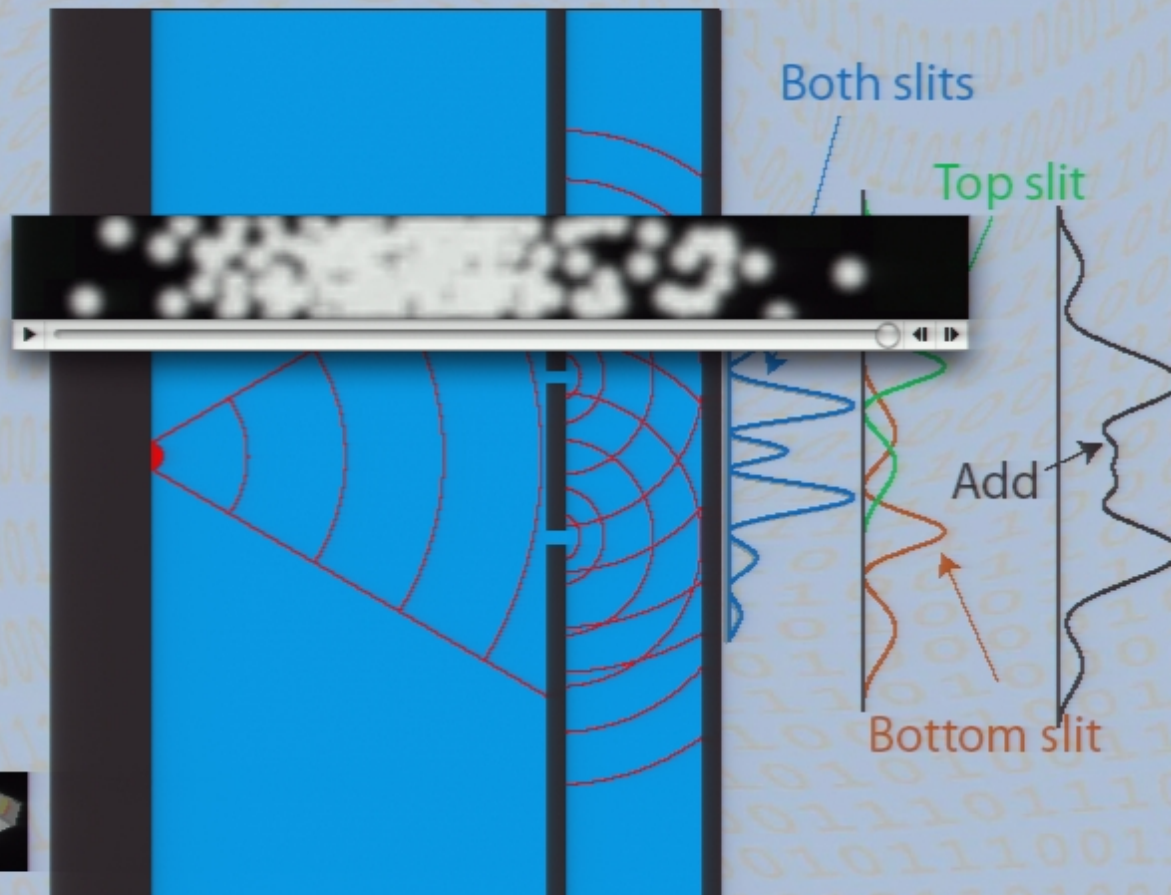
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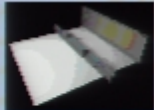
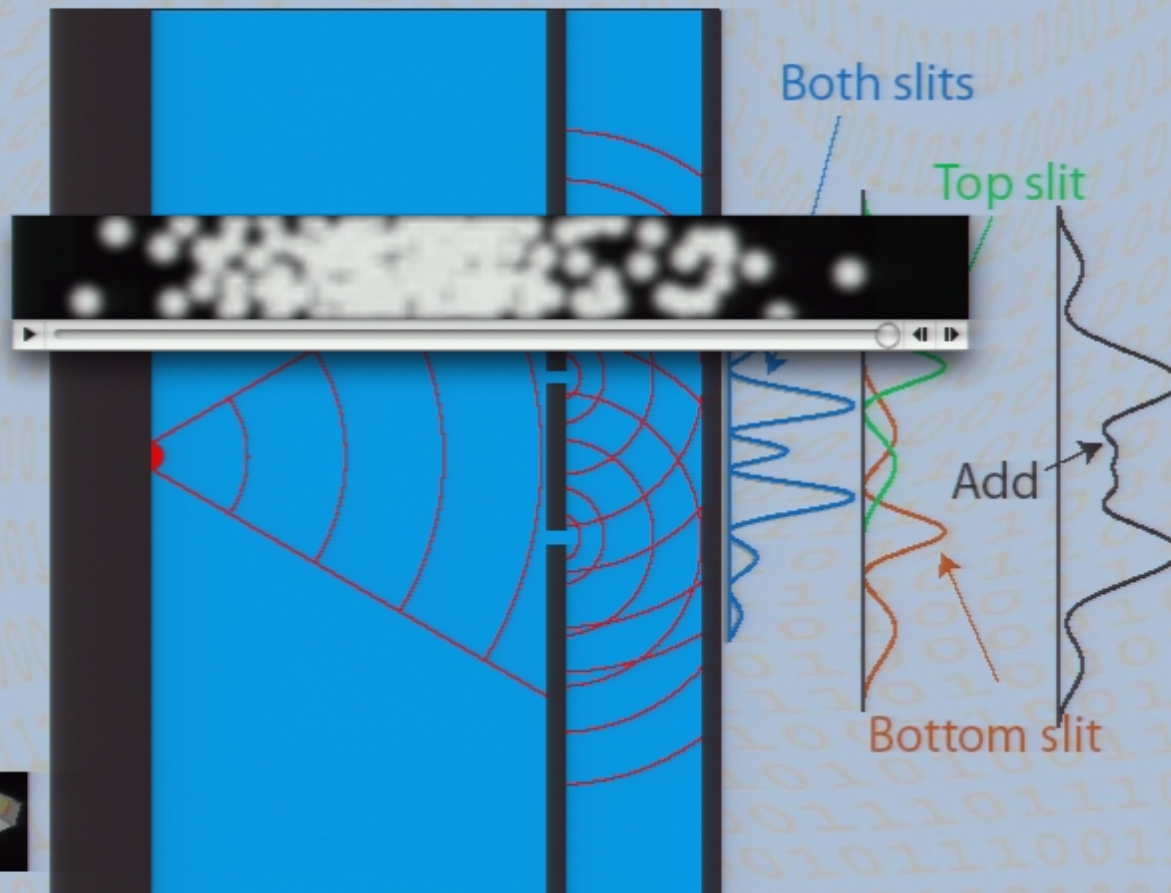
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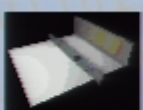
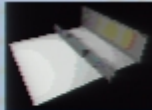
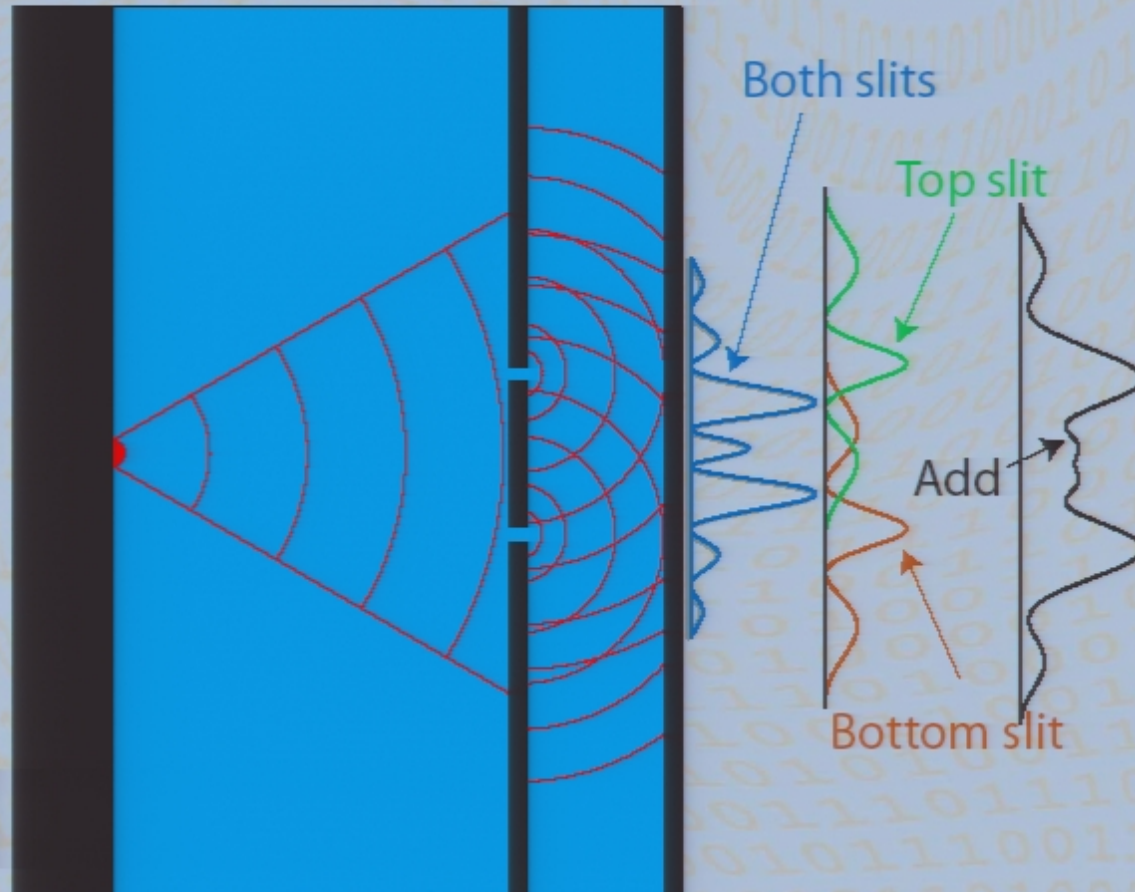
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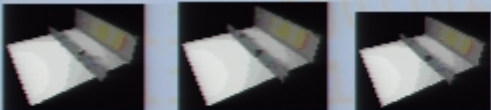
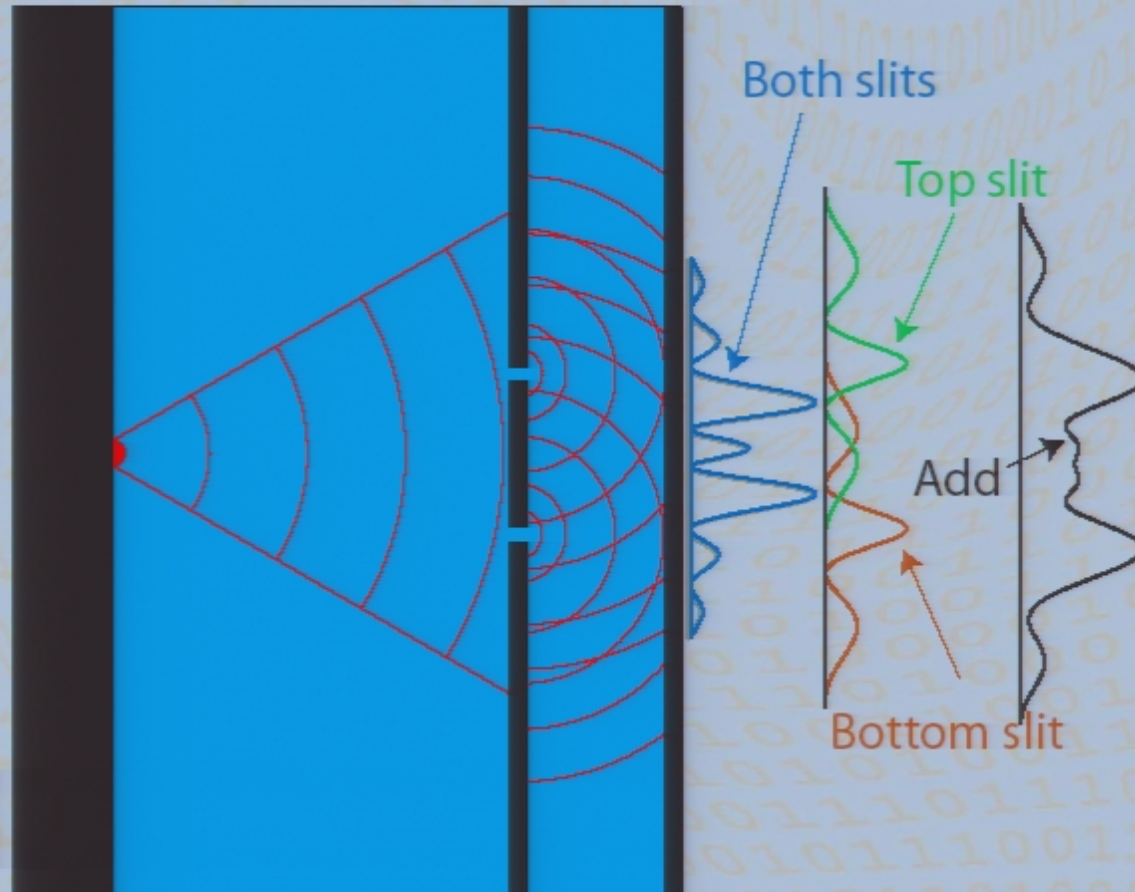
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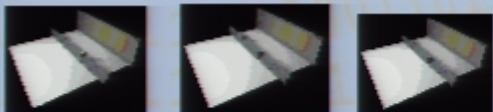
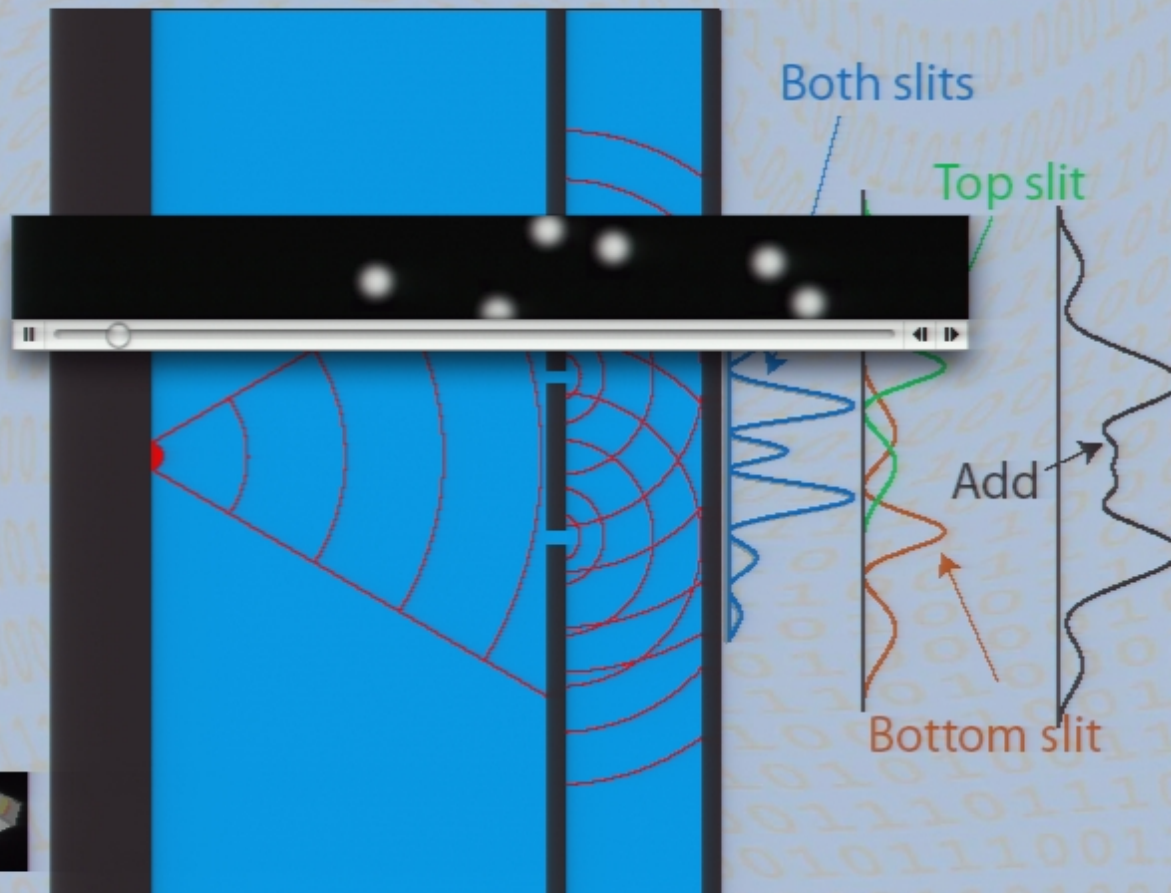
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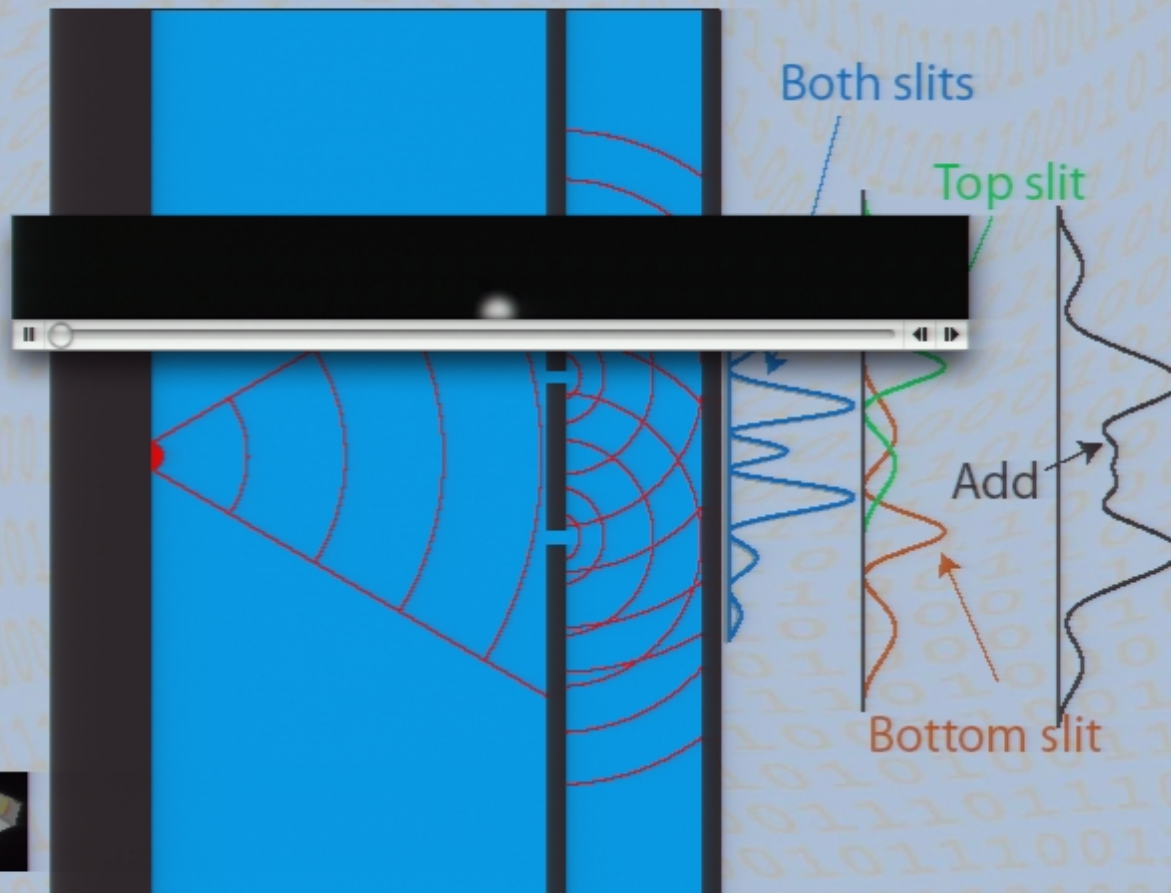


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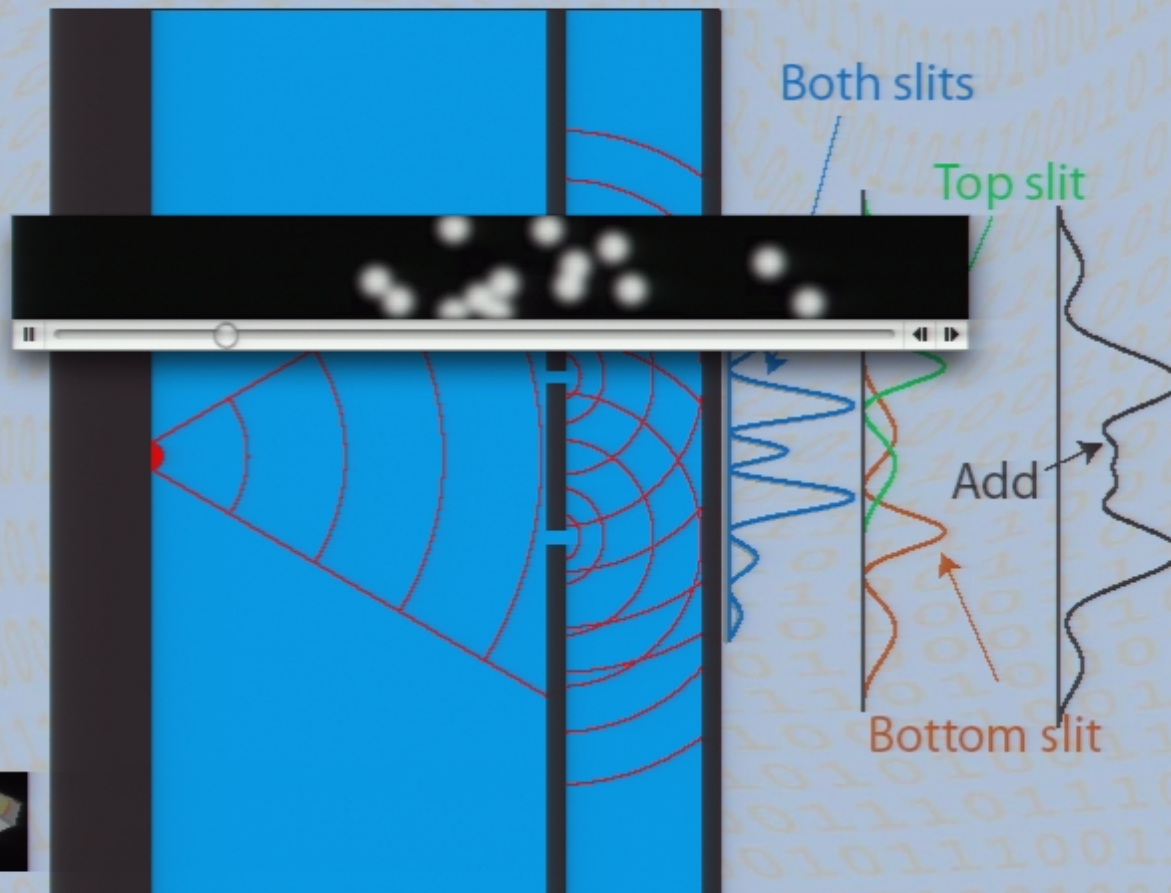


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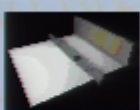
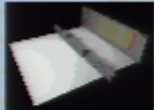
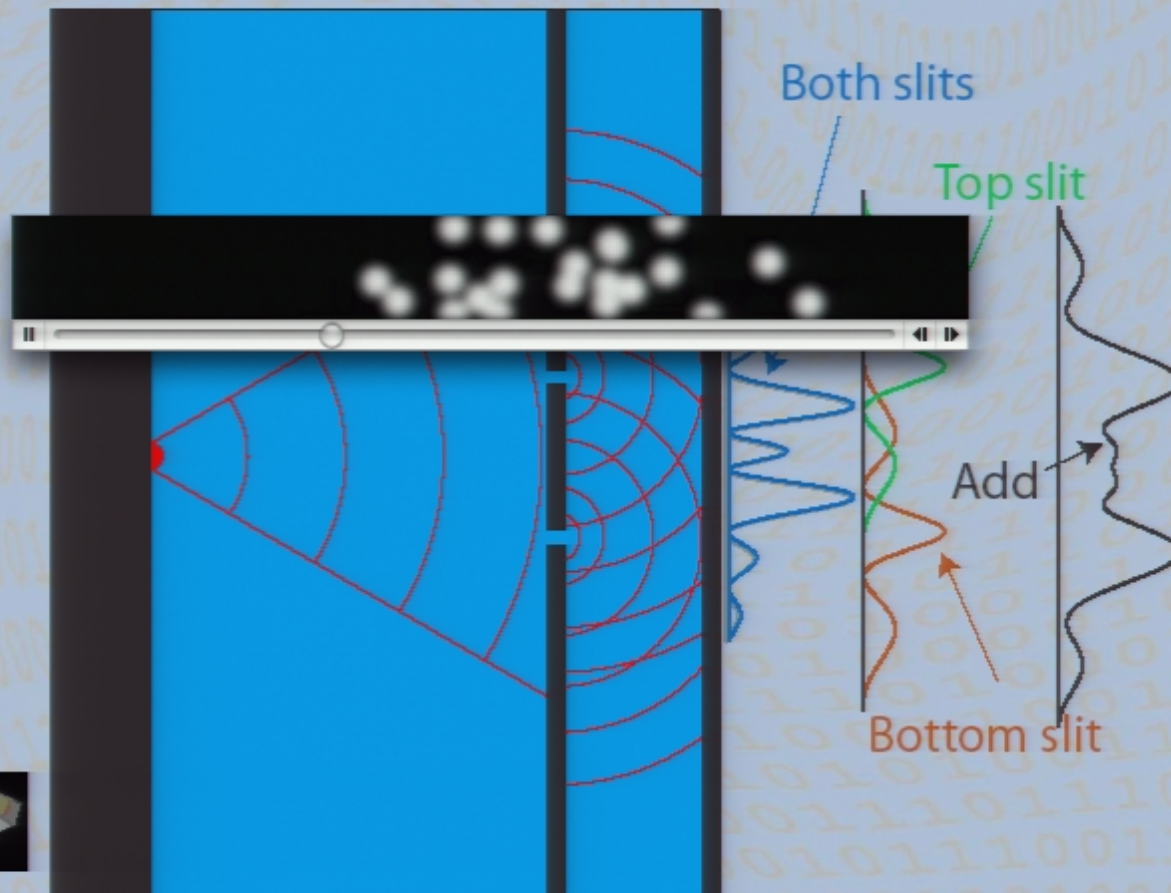
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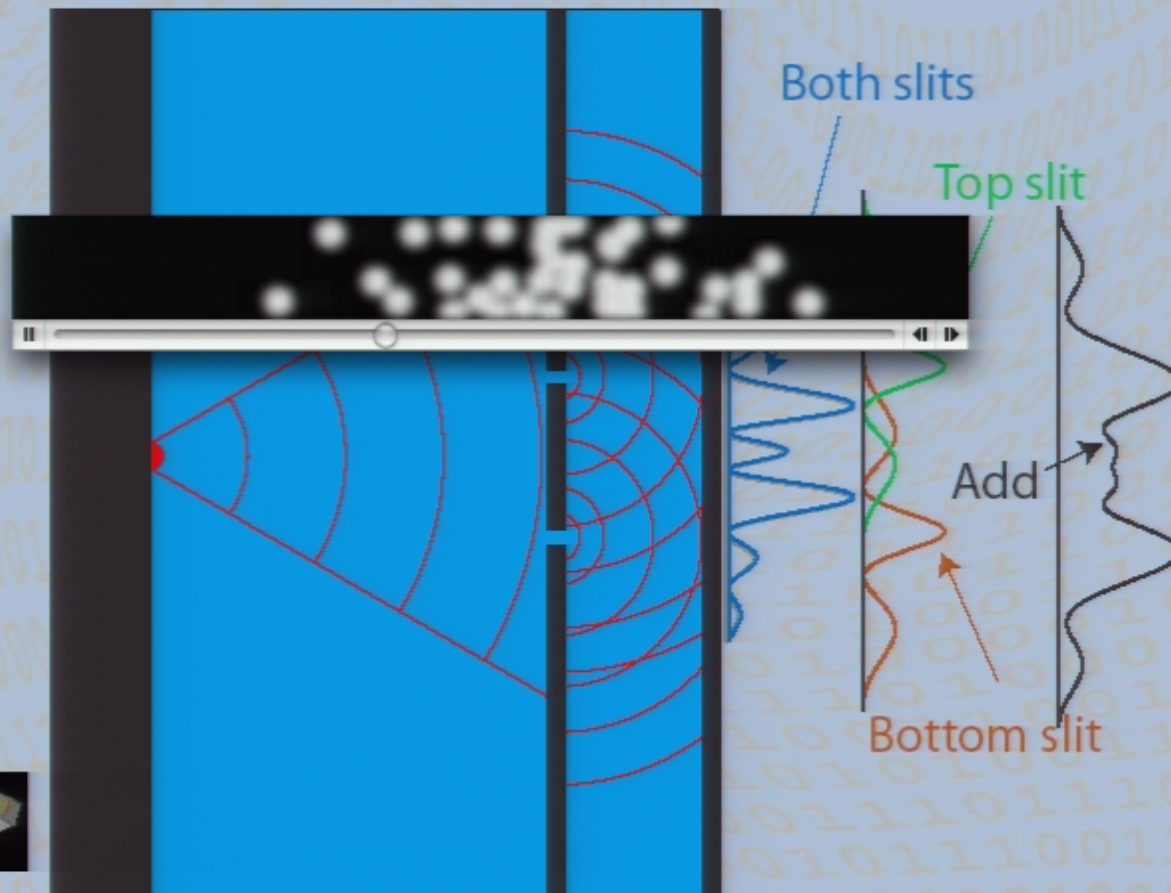
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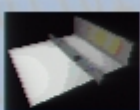
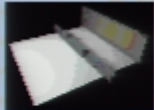
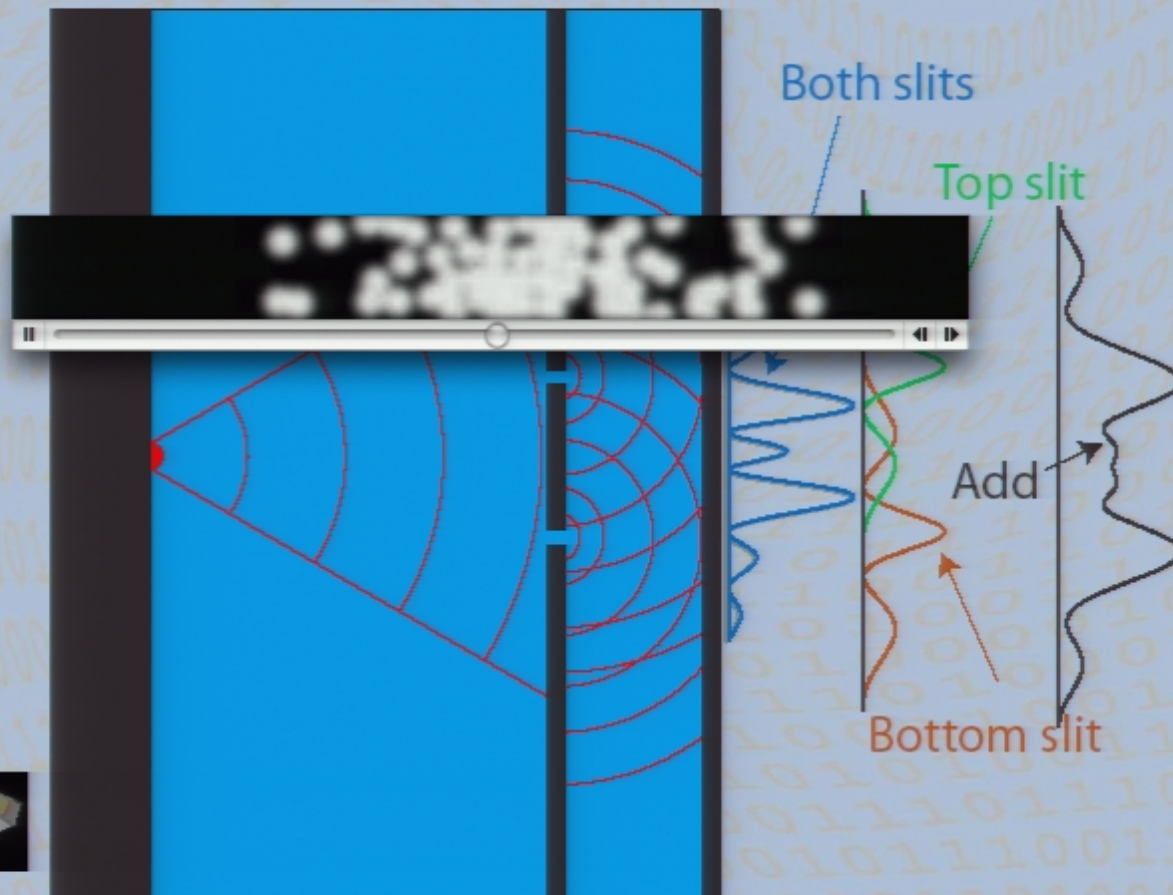
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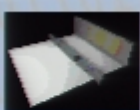
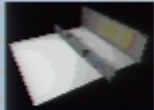
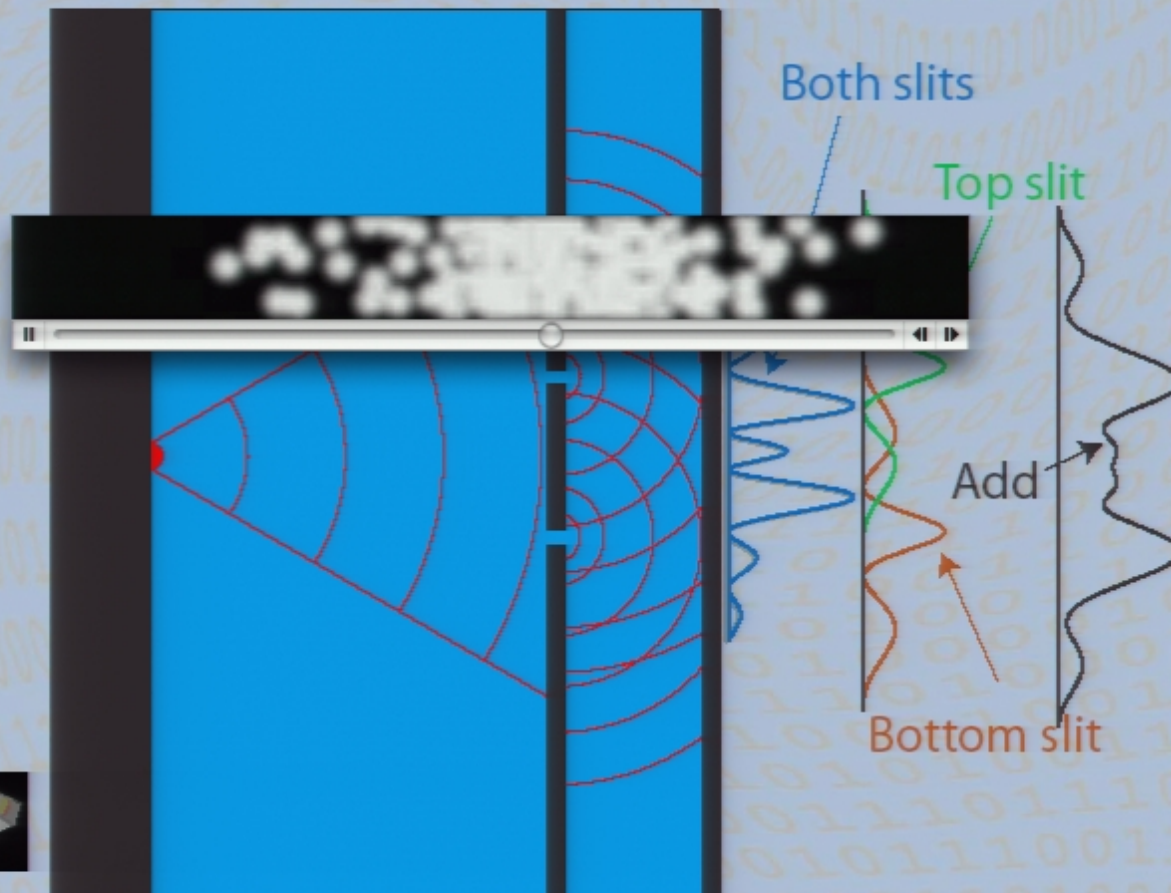
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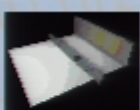
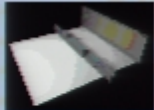
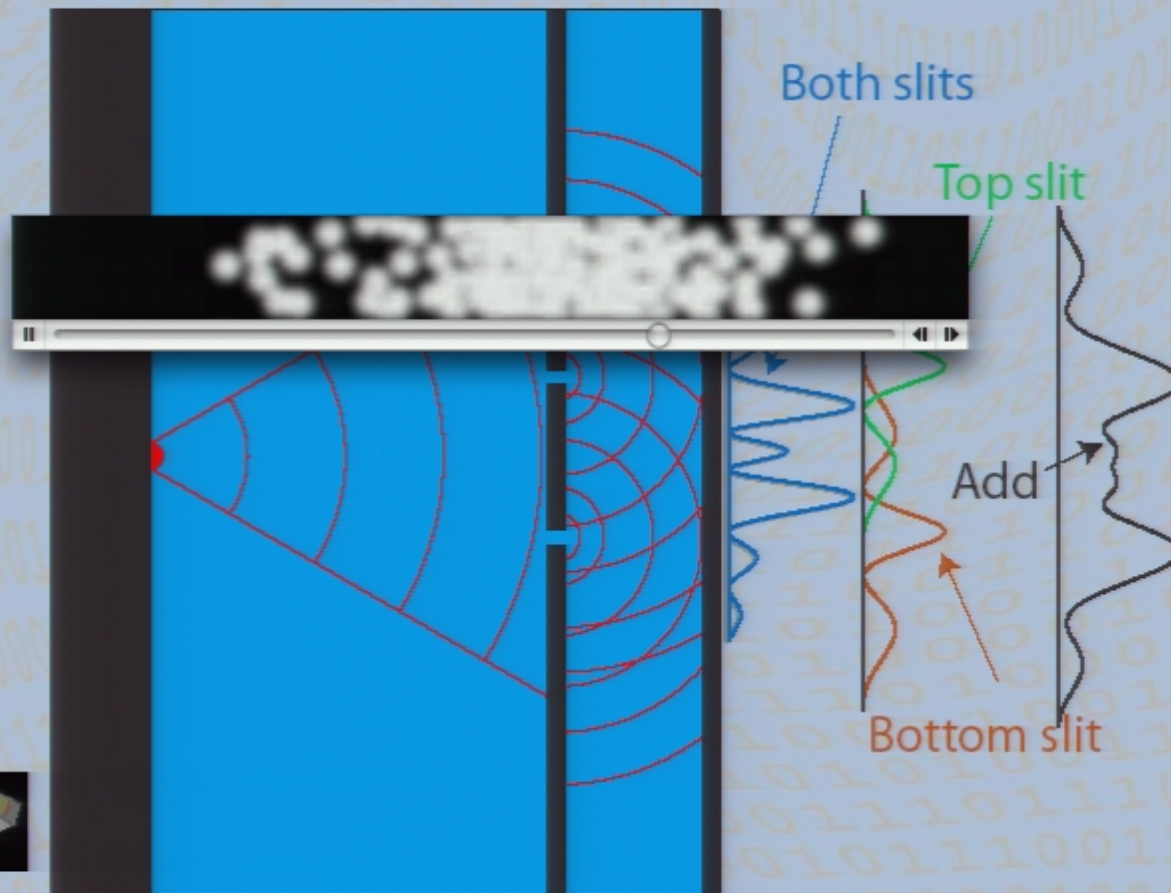
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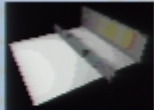
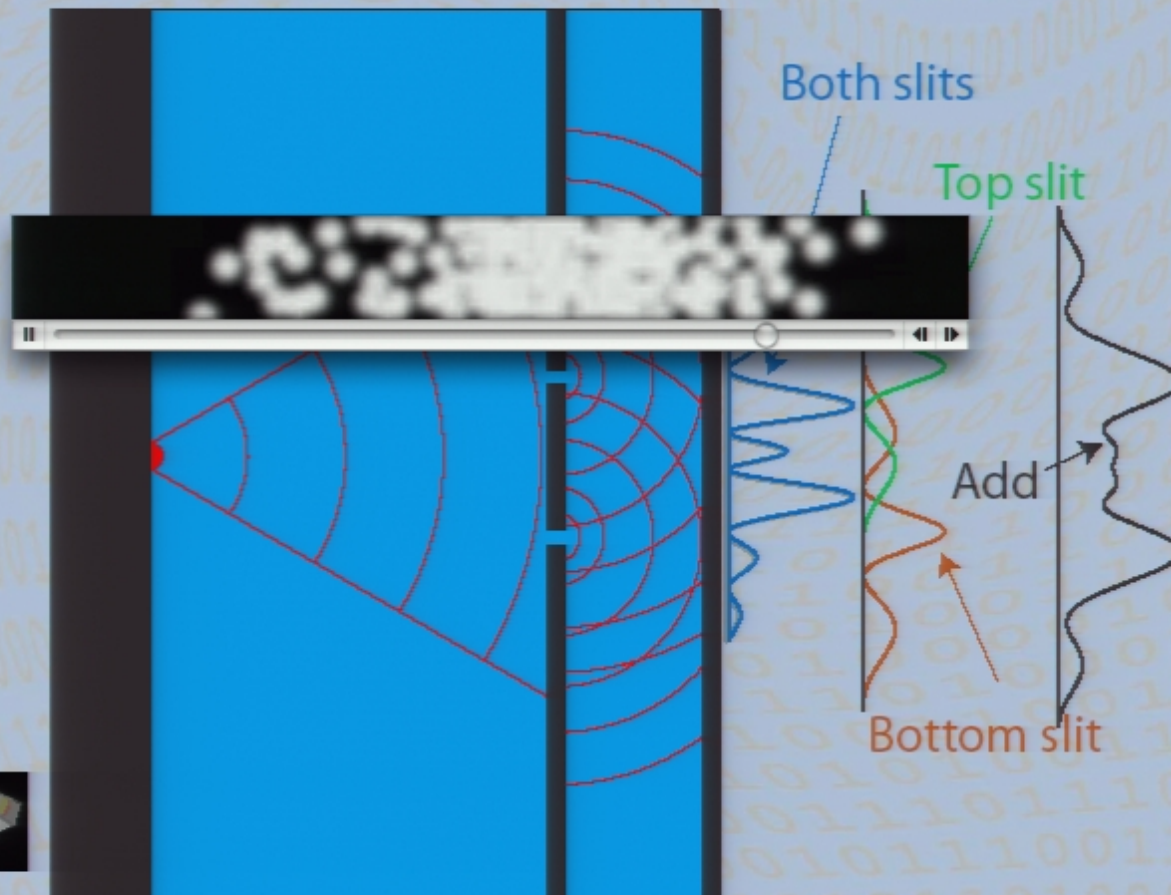
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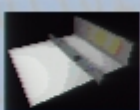
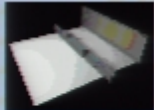
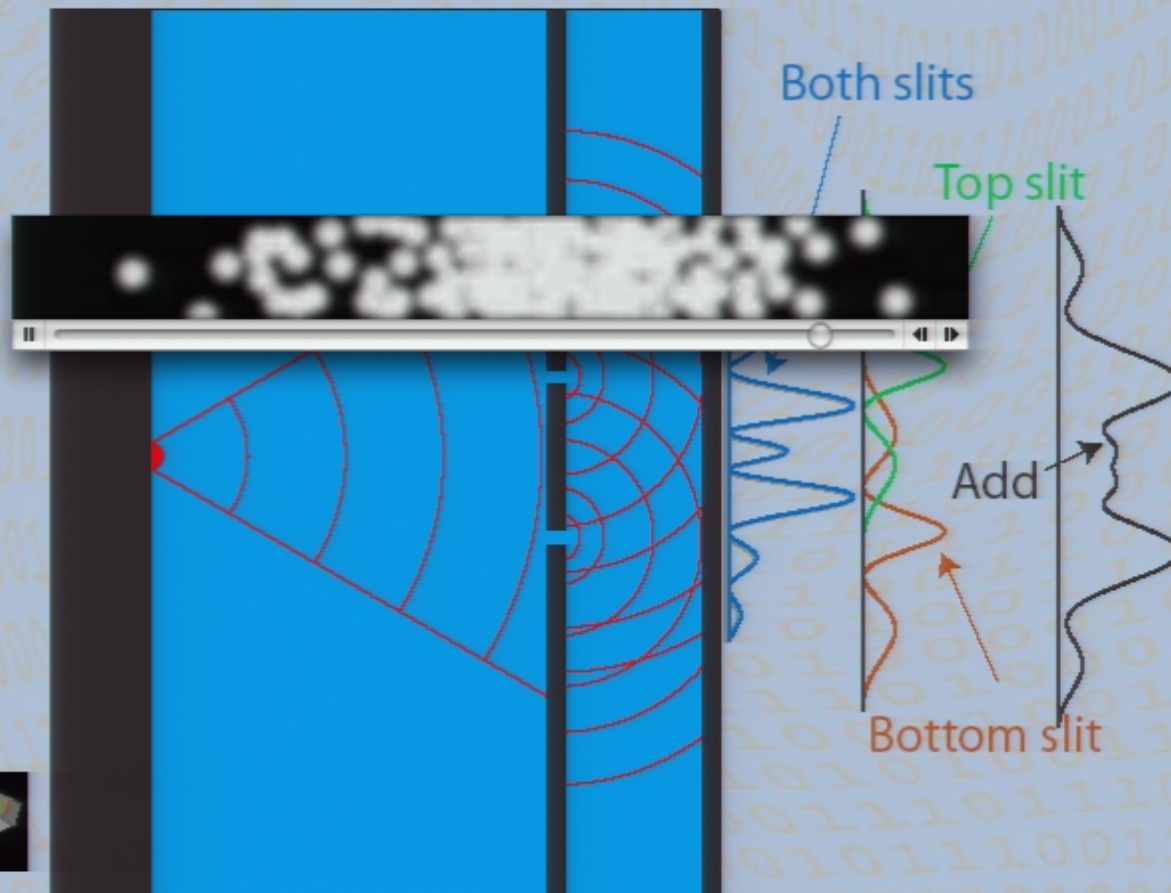
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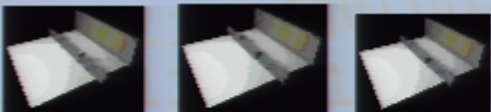
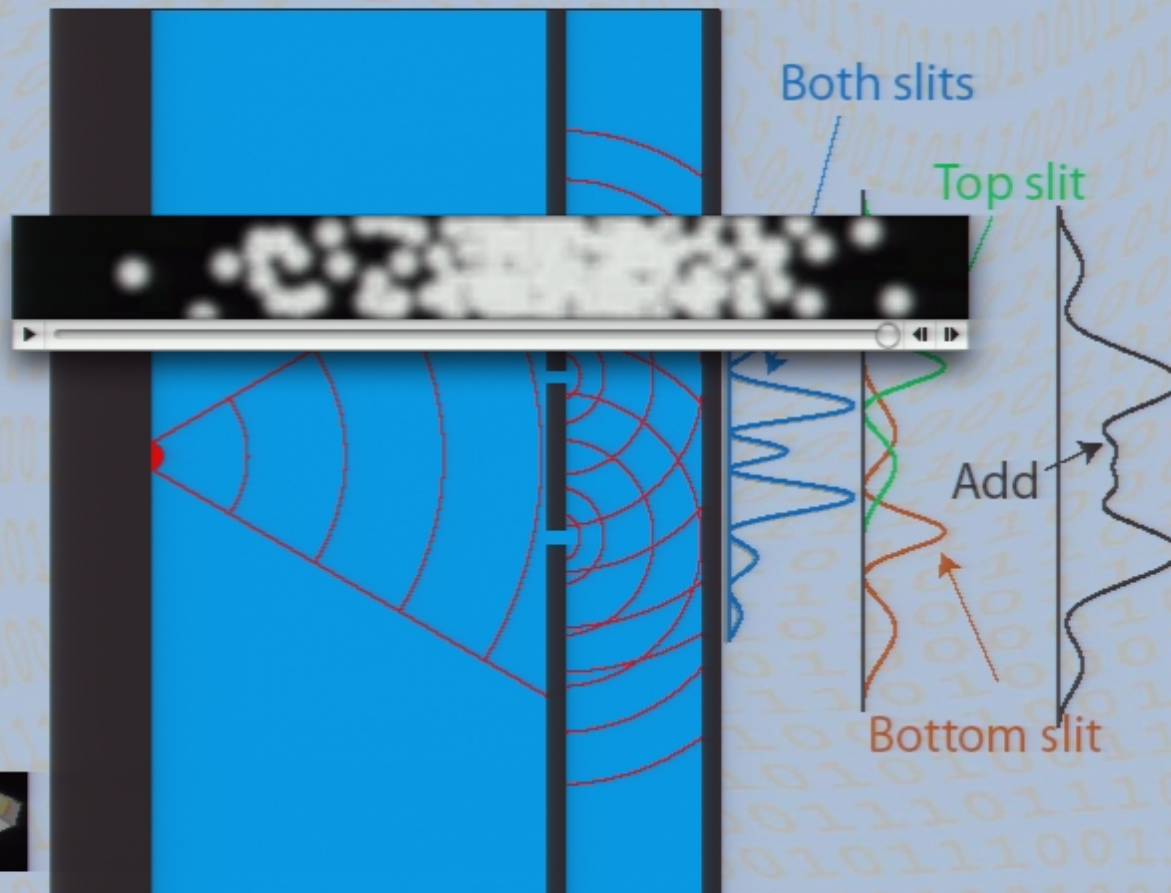
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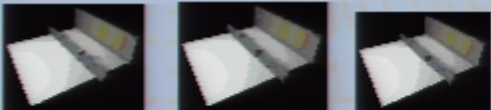
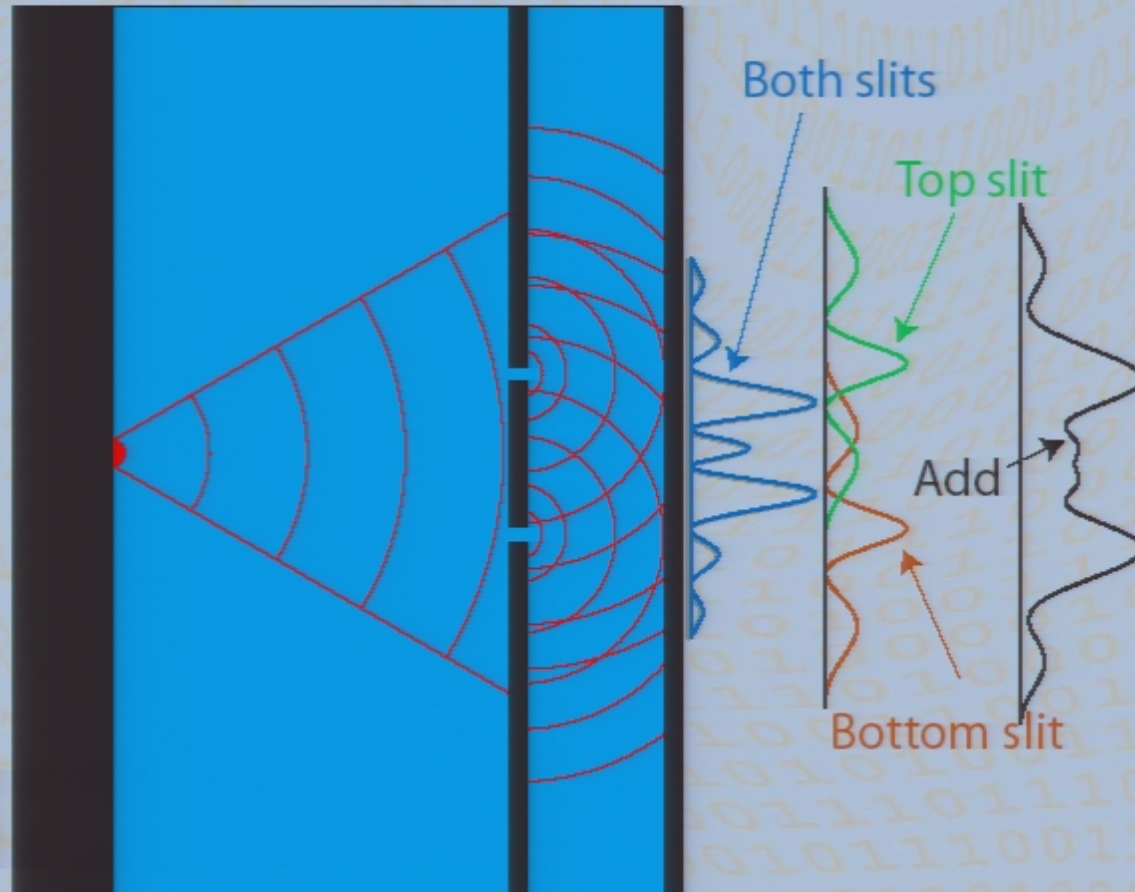
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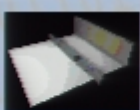
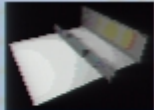
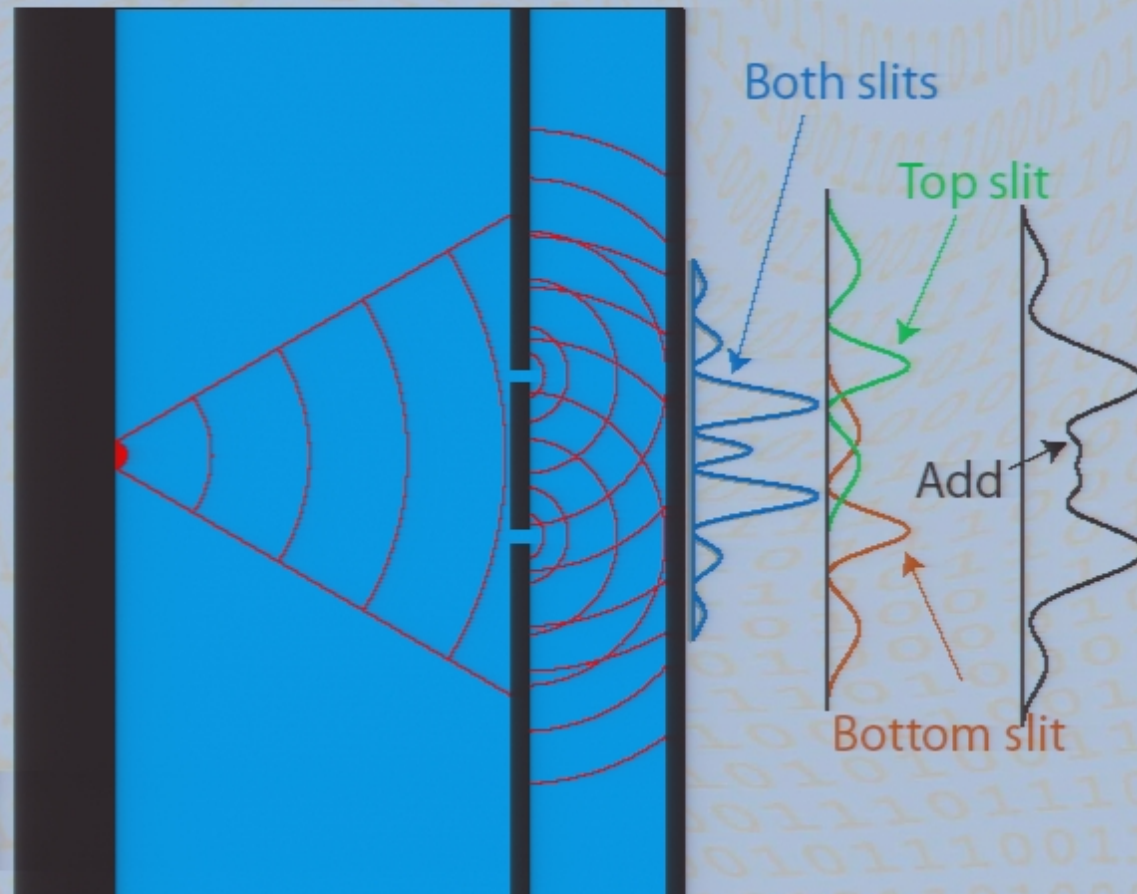
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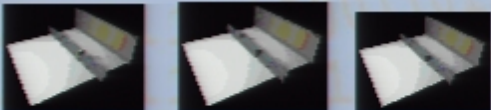
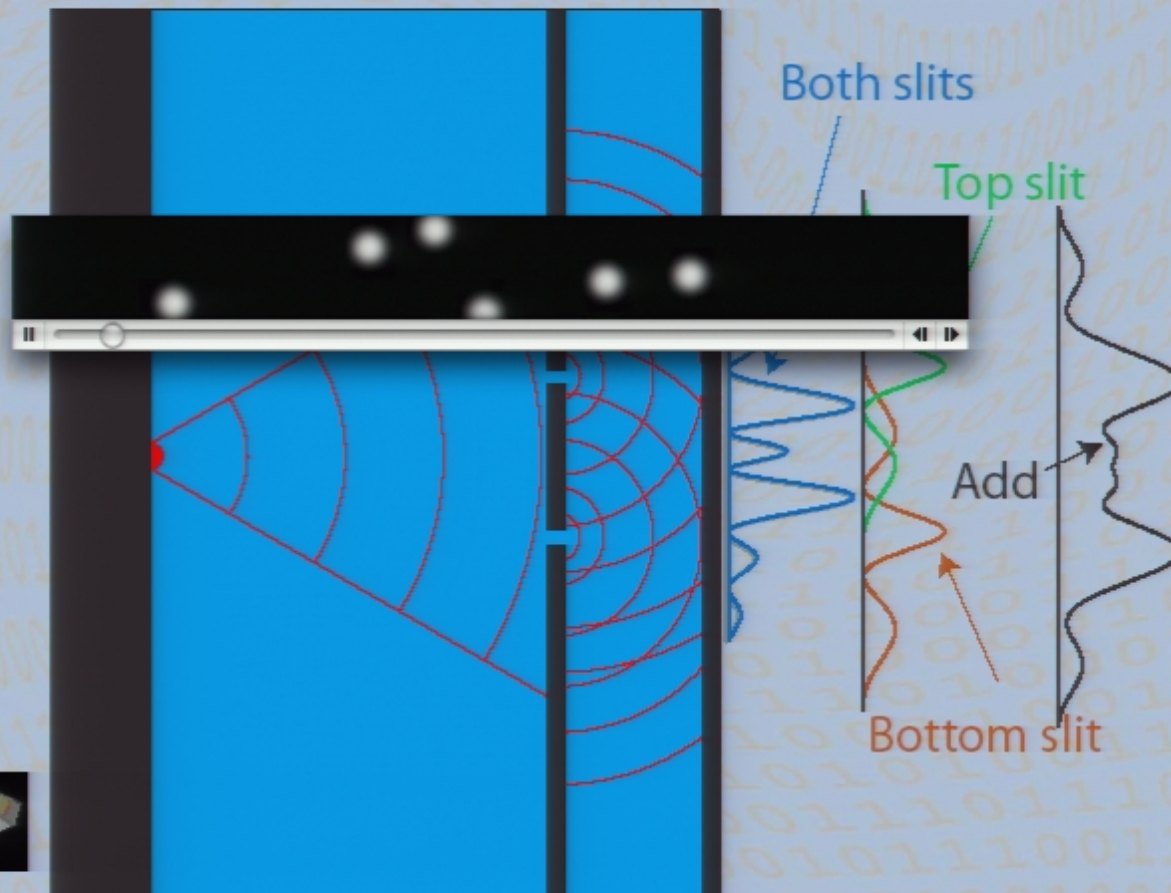
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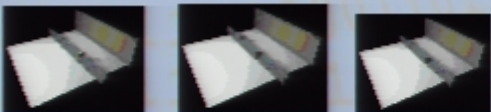
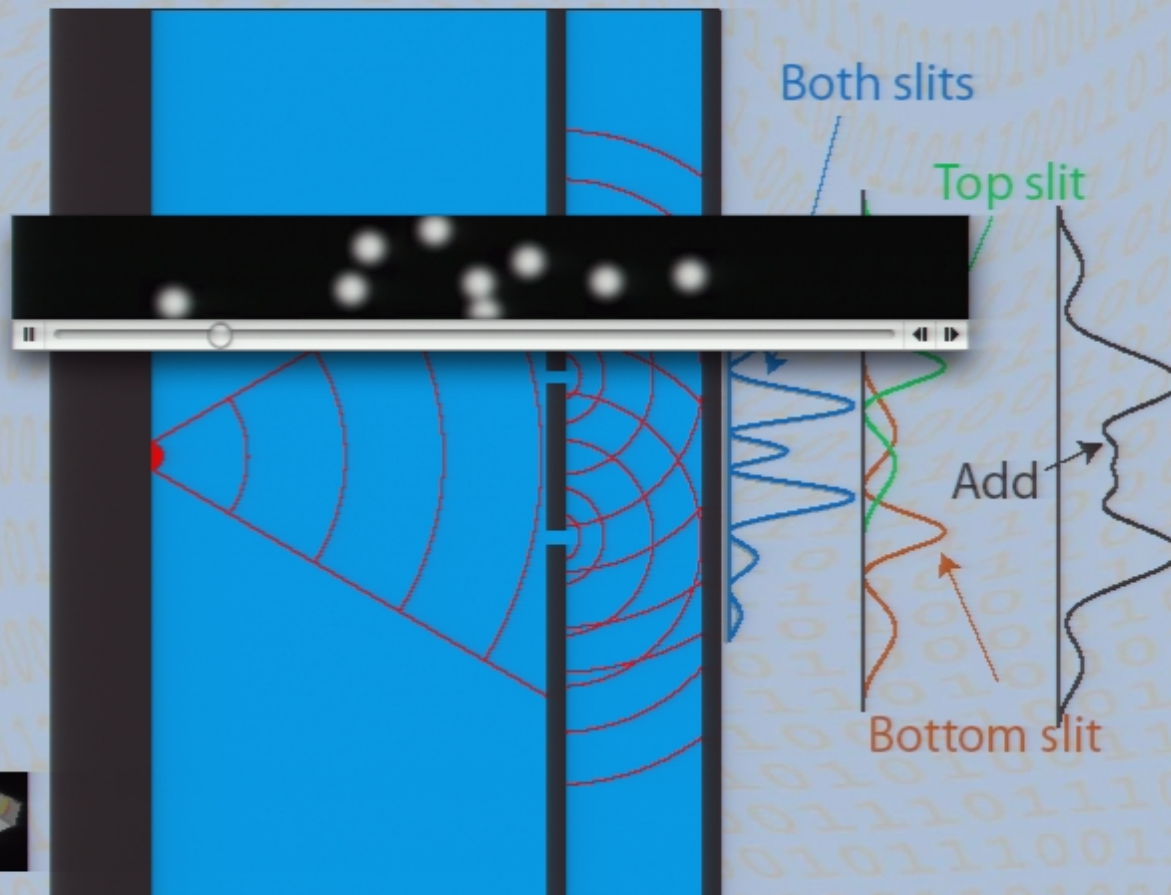
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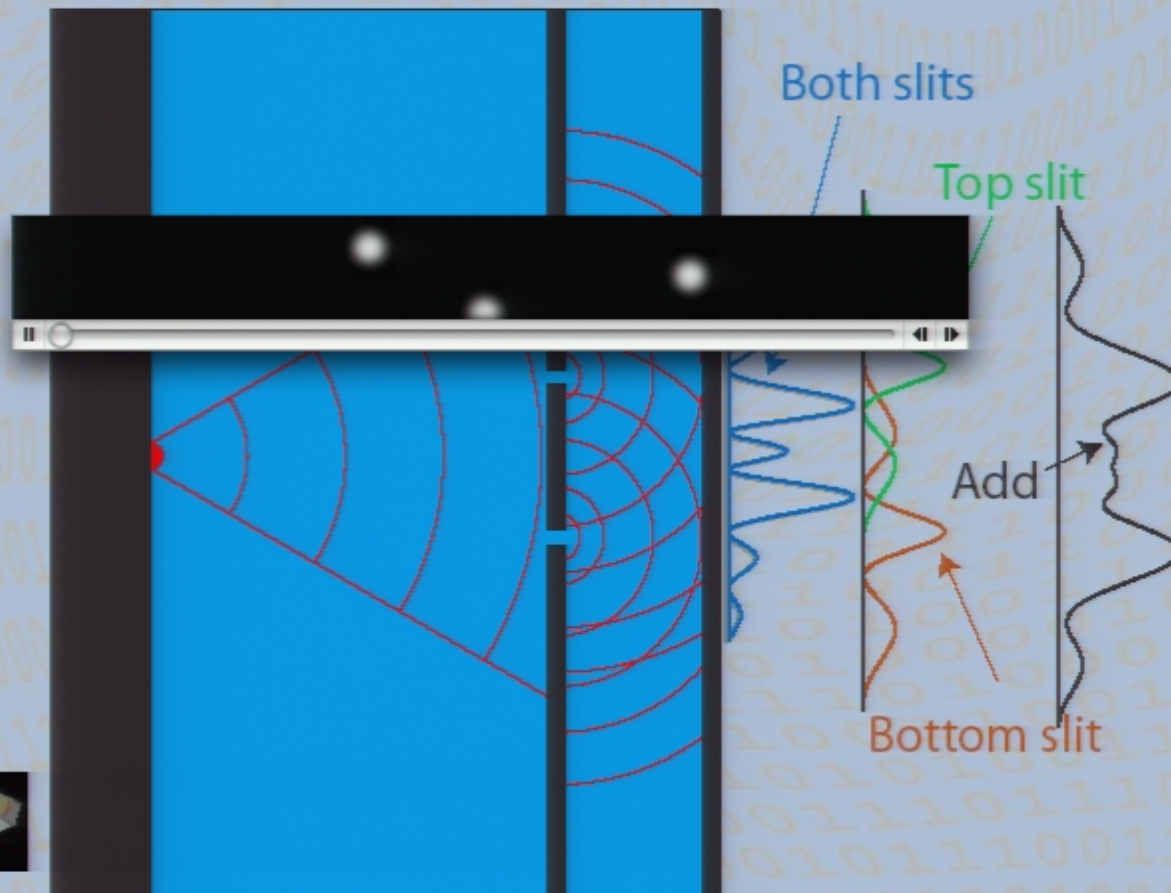
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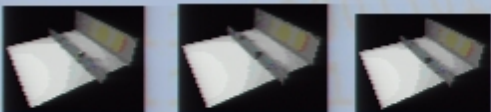
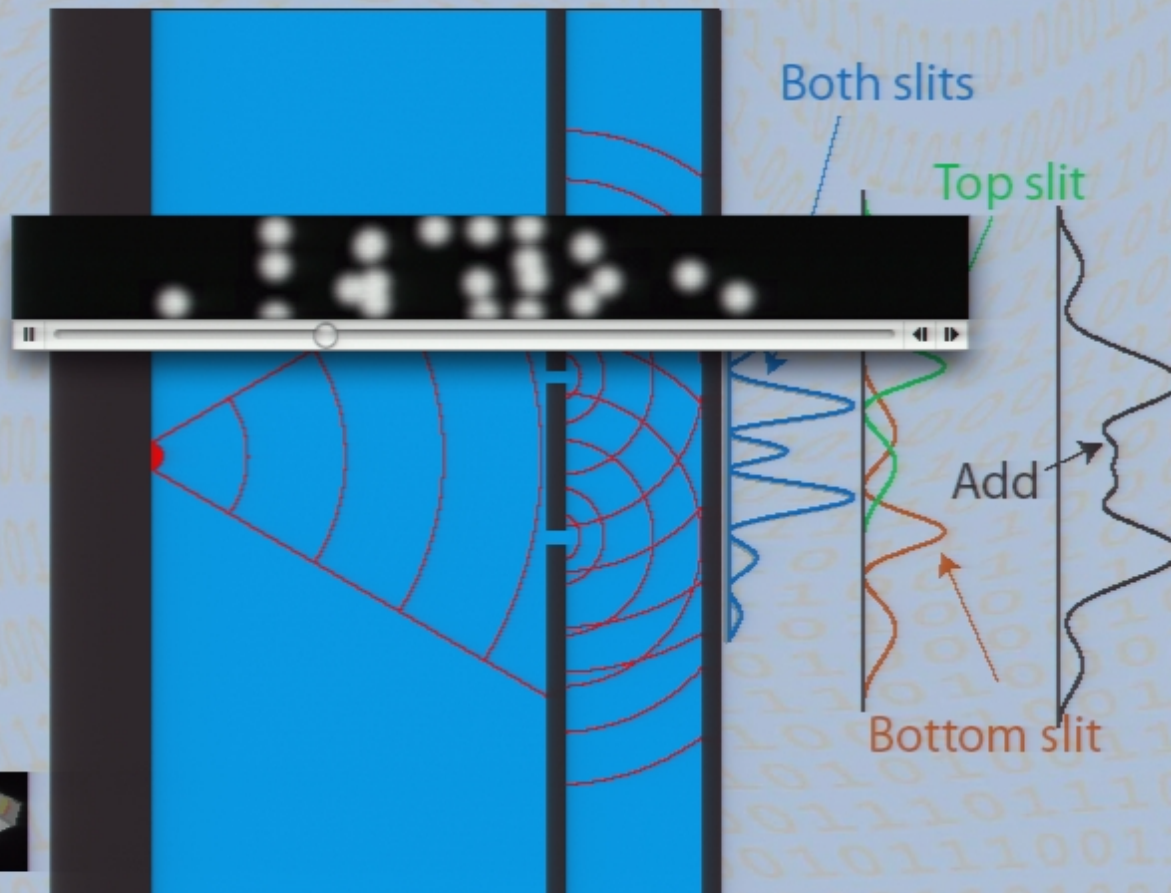
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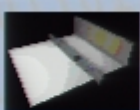
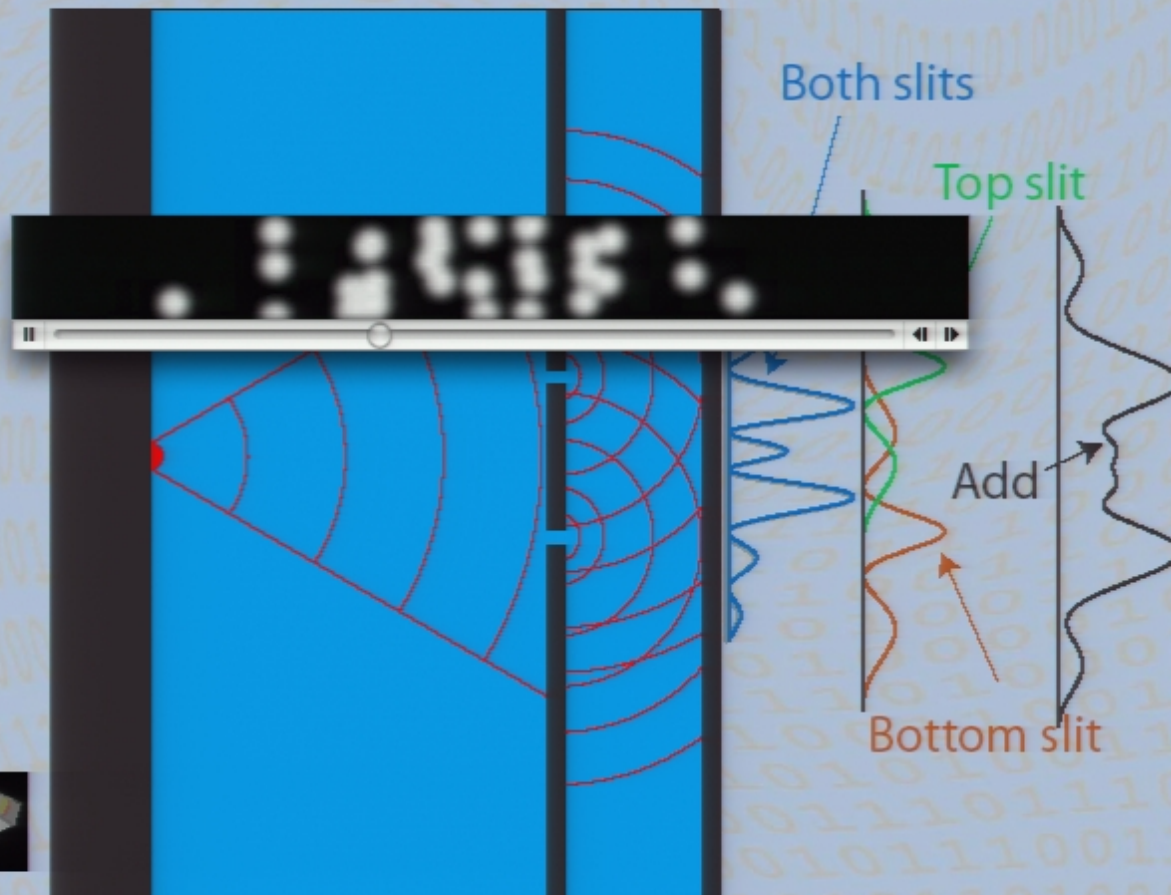
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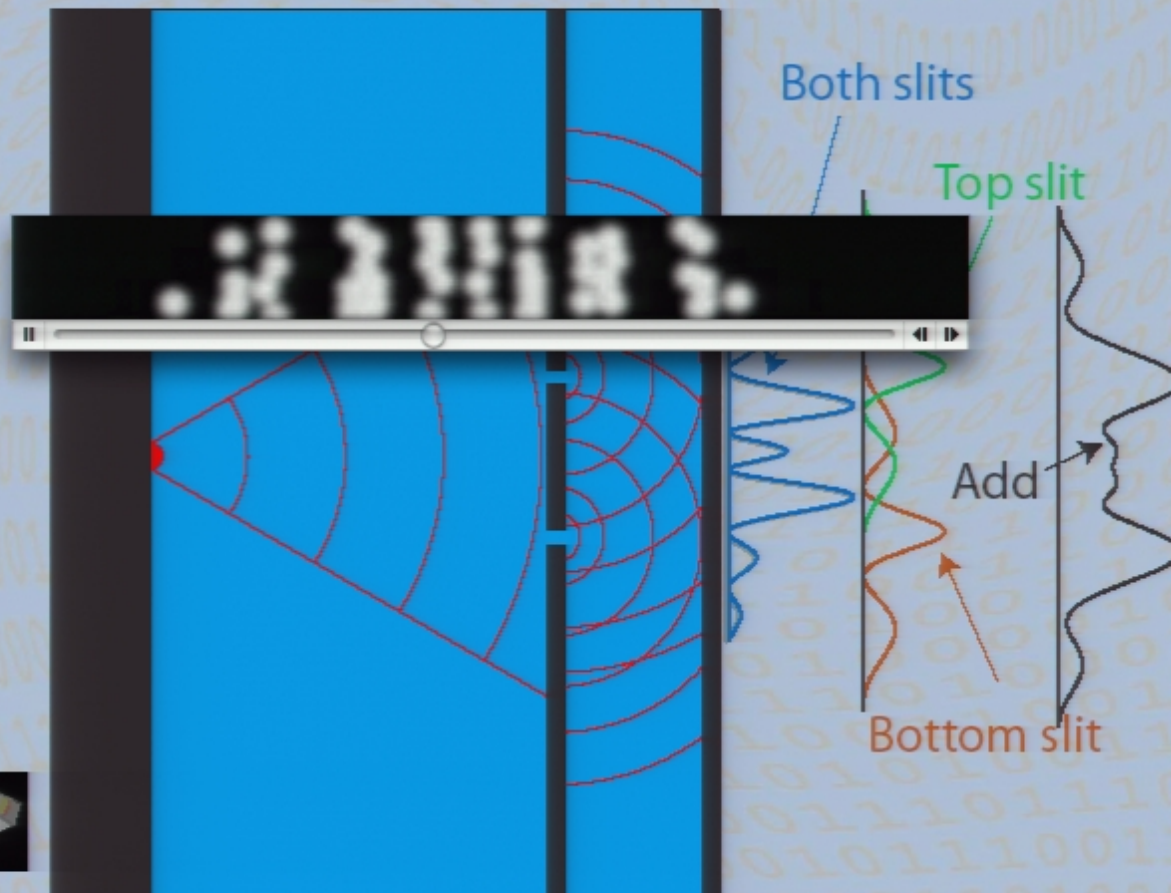


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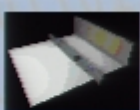
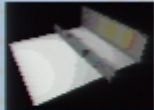
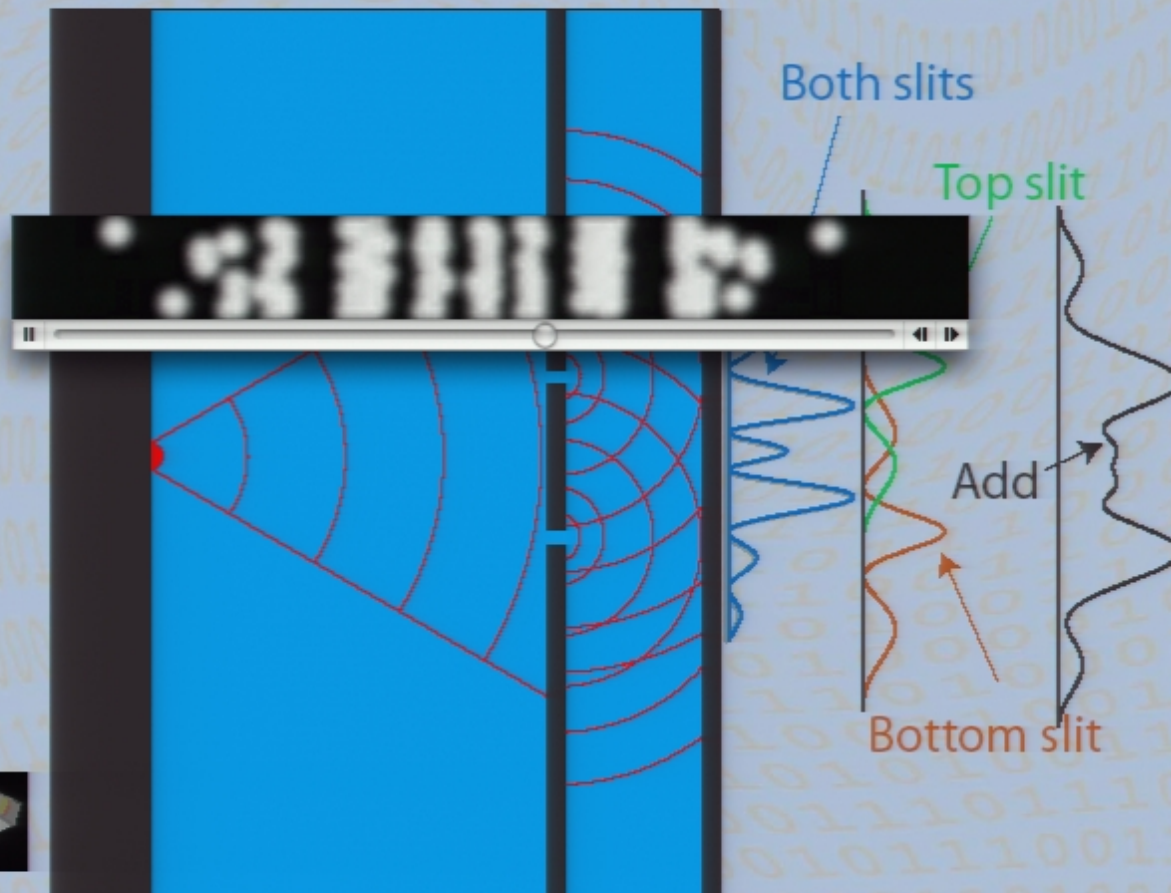


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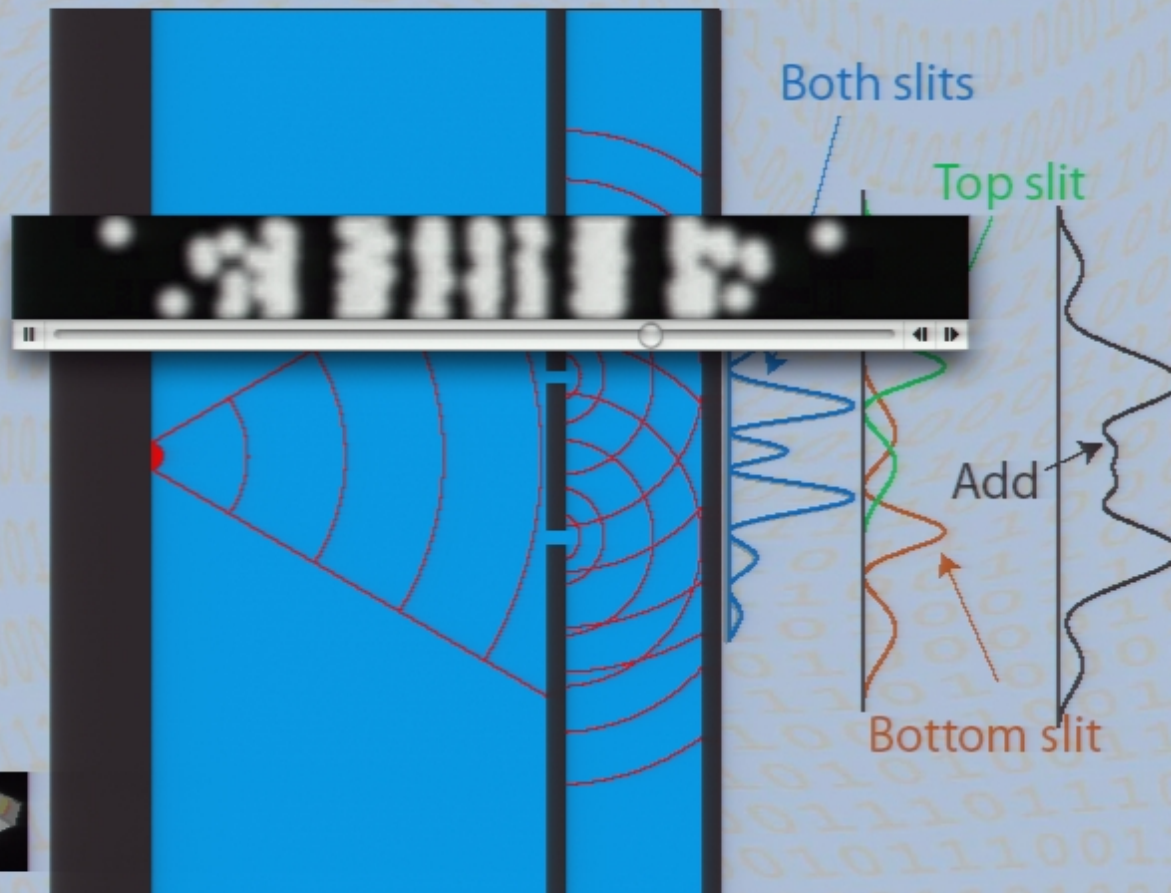
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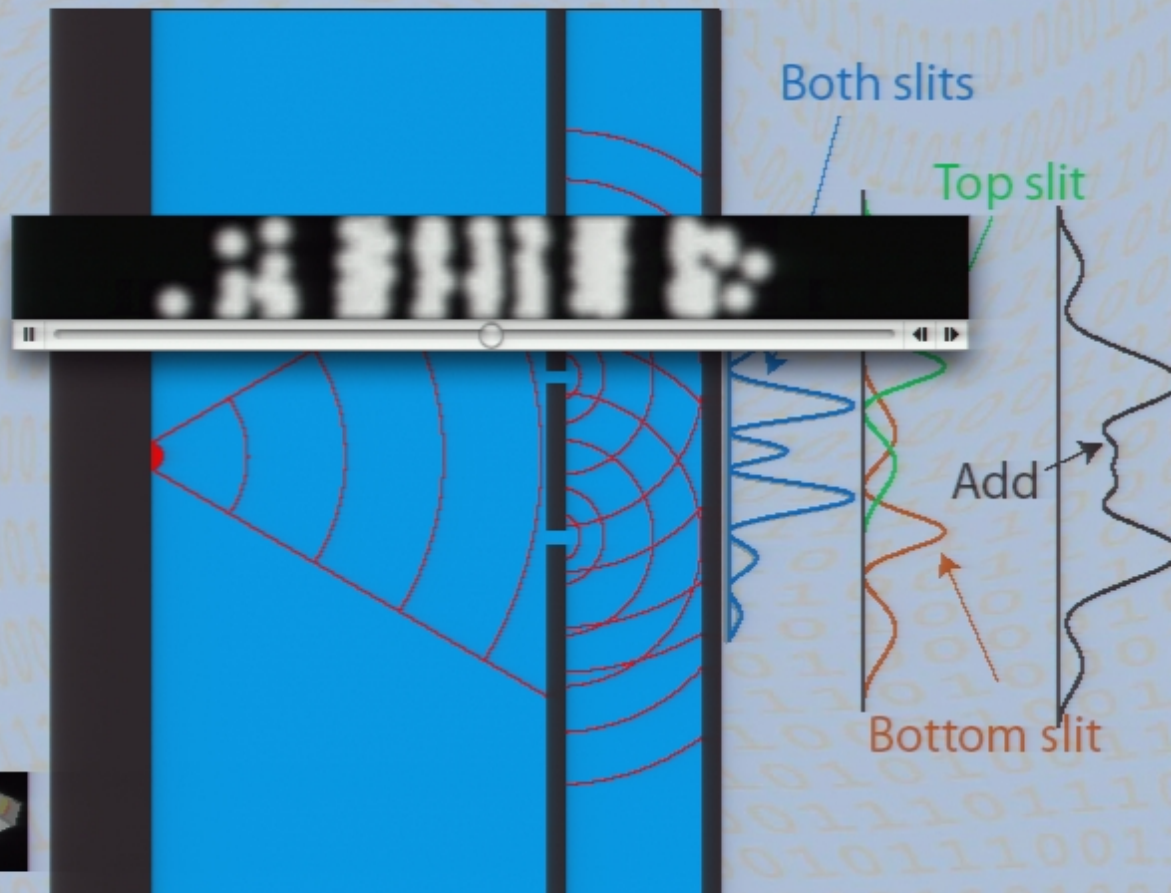
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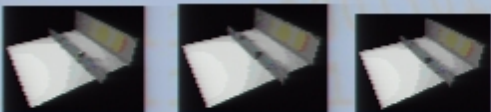
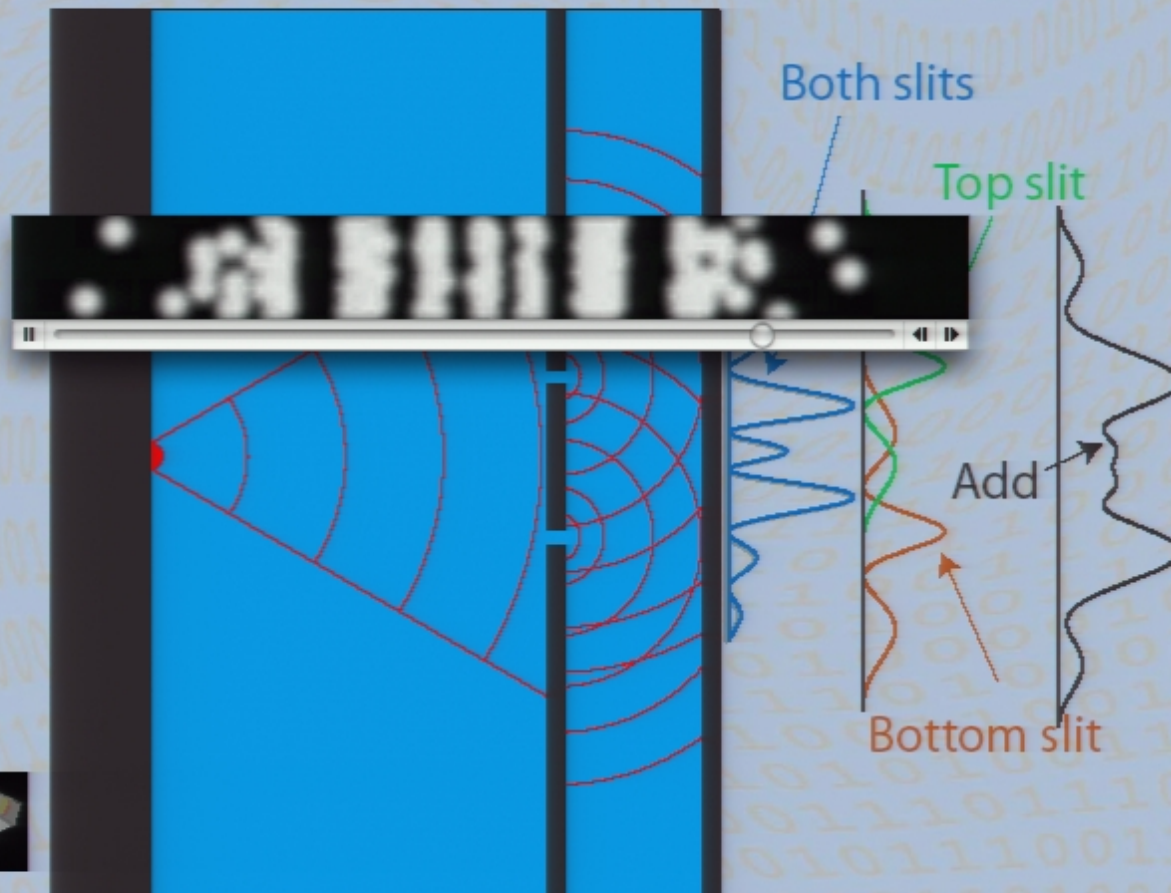
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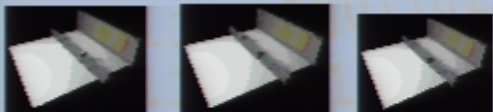
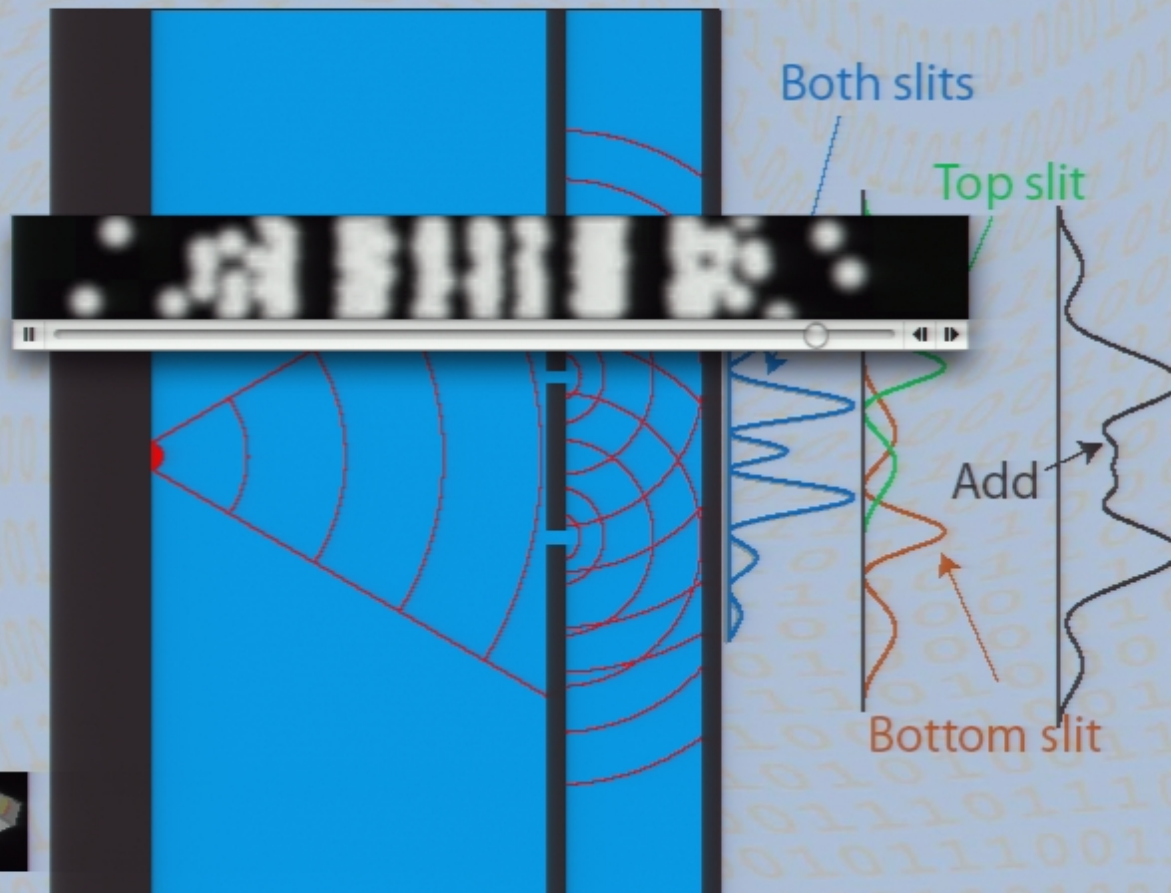
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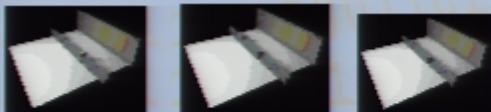
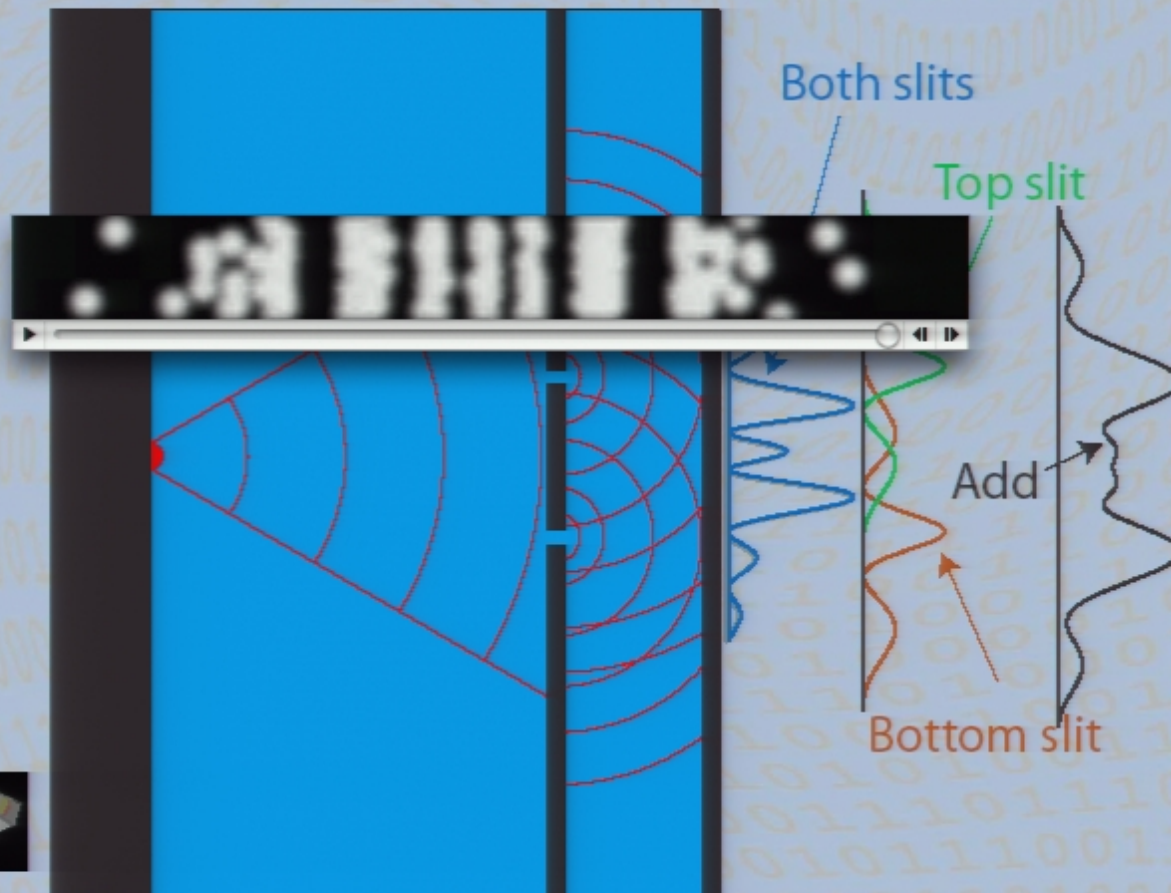
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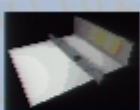
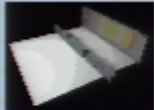
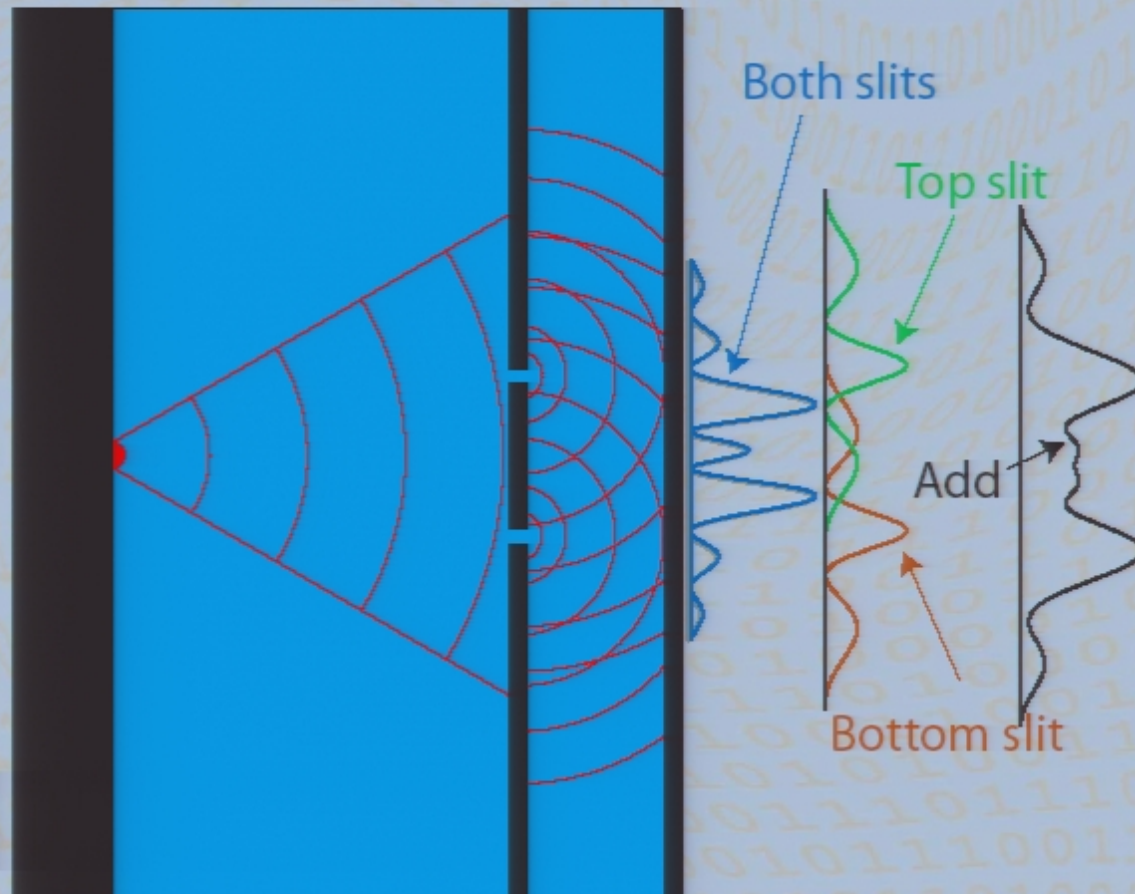
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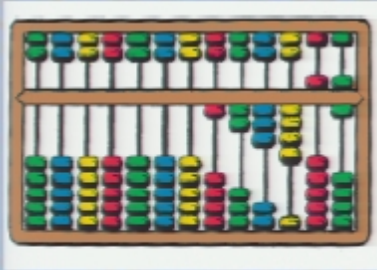
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Two properties of Quantum Mechanics:

- 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.

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

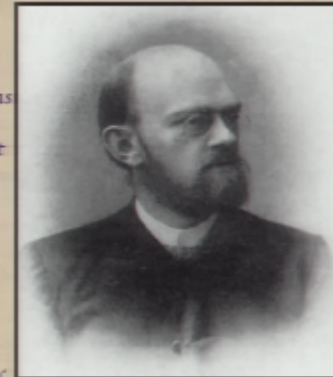
When we are engaged in investigating the foundations of a science, we must set up a system of axioms which contains an exact and complete description of the relations subsisting between the elementary ideas of that science. The axioms so set up are at the same time the definitions of those elementary 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 thereupon 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 them⁴ 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 those, 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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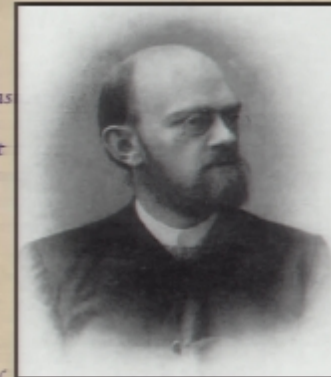
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This statement is false

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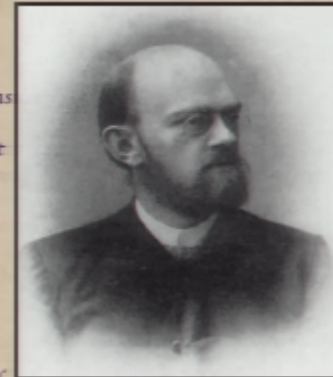
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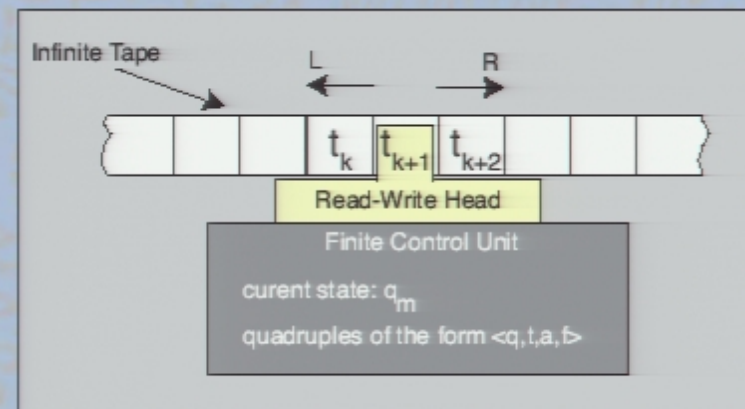
Turing machines



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

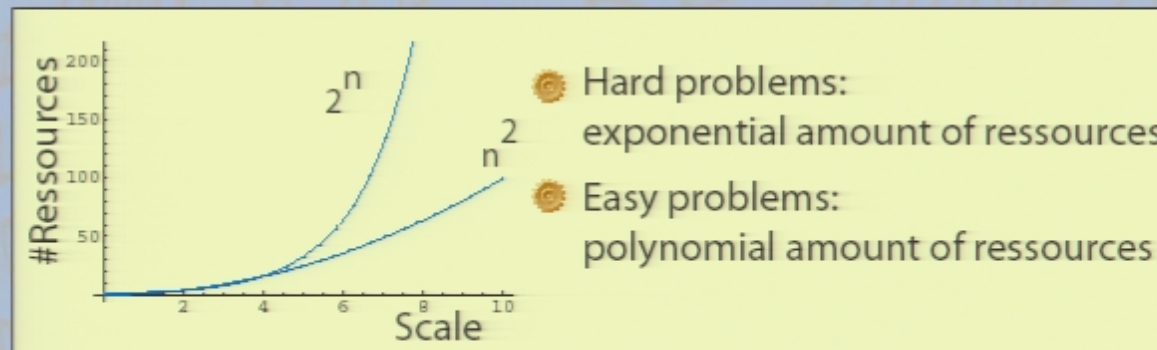
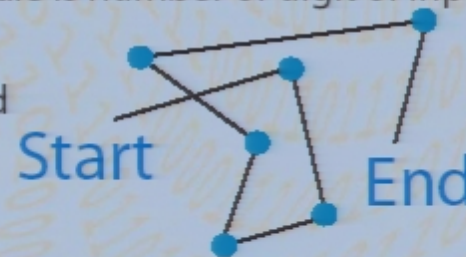
→ **Factor in product of primes:** $54029 = 97 \times 557$

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)

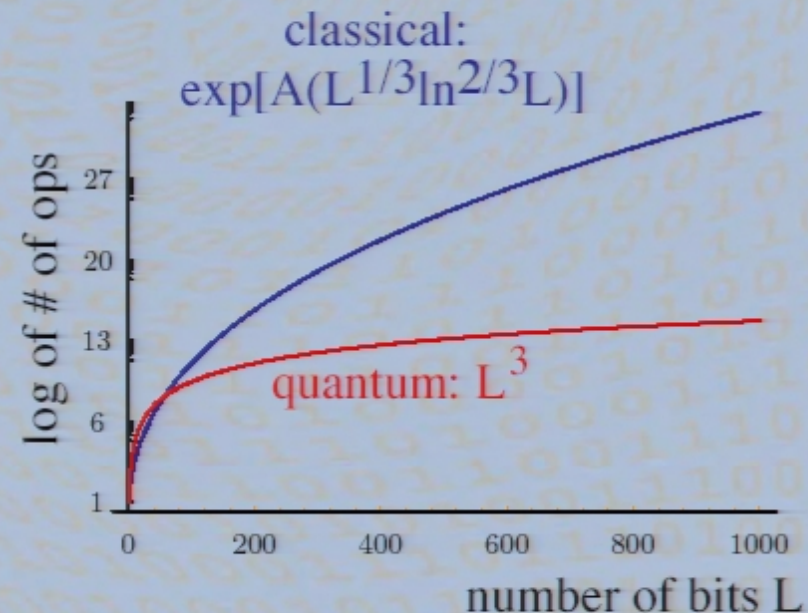
$$n=pq \quad (L = \ln n)$$

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

Quantum algorithm

of gates $\sim 12L^3$

of qubits $\sim 5L$



Complexity theory

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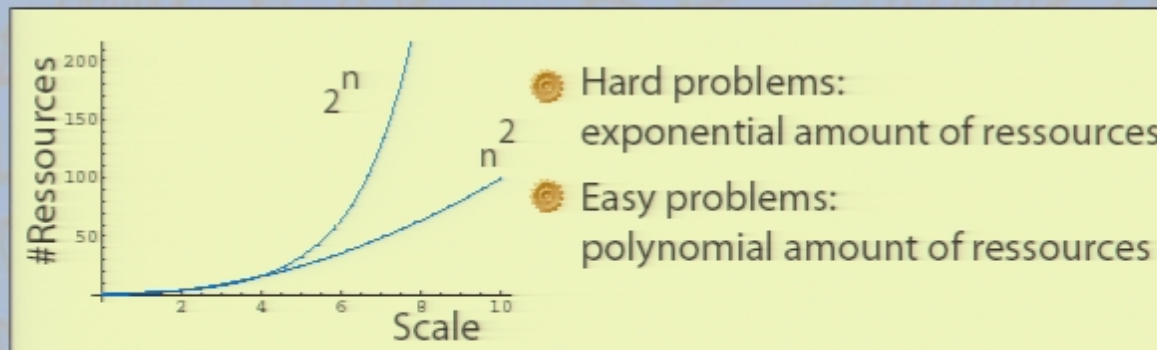
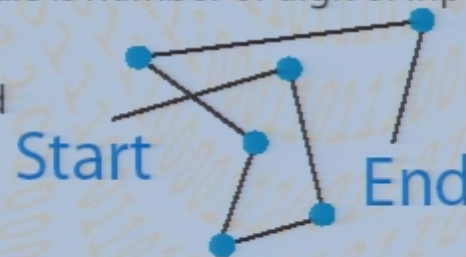
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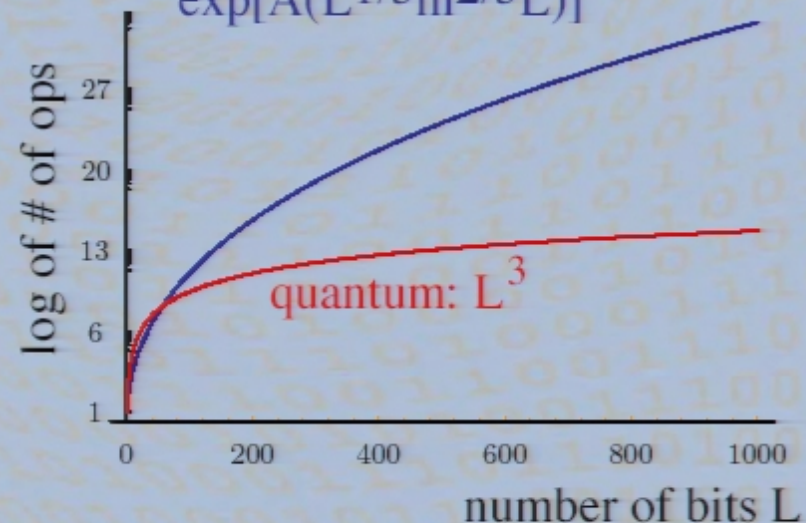
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Quantum algorithm

of gates $\sim 12L^3$

of qubits $\sim 5L$

classical:
 $\exp[A(L^{1/3}\ln^{2/3}L)]$



William T. Tutte



Colossus, the first electronic computer,
was used to break FISH



Distinguished Professor Emeritus at UW

The difficulty of simulating a Quantum Computer

=

evaluating a Tutte polynomial

A classical computer in a nutshell

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

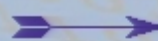
...110	→	...001
01000		01100
11101		00101
000...		010...

- 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

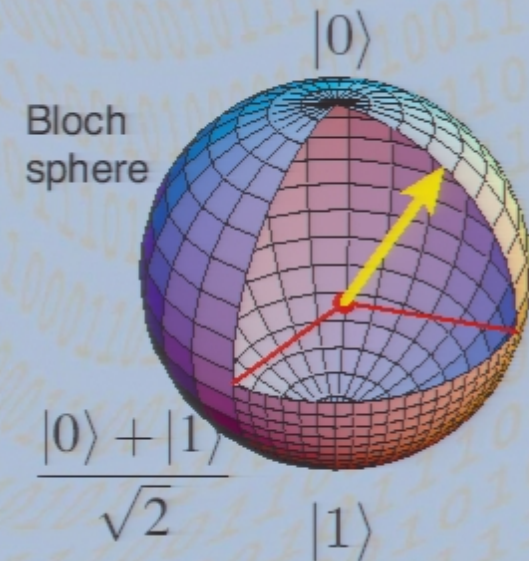
in out

A quantum computer in a nutshell

Quantum bits (qubits) are quantum systems with two levels

$$\text{Qubit} = 0.95 \left(\uparrow = 1 \right) + 0.3 \left(\downarrow = 0 \right)$$

$$\text{Atom} = 0.95 \left(\text{State 1} \right) + 0.3 \left(\text{State 2} \right)$$



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

of classical
bits

$2^1 = 2$

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

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



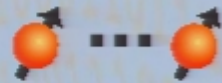
0000,0001,...,1111

$2^4 = 16$

⋮

⋮

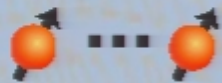
10



0000000000,...

$2^{10} = 1\text{k}$

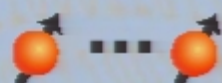
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0000000000....,

$2^{20} = 1\text{M}$

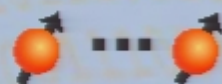
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0000000000....,

$2^{30} = 1\text{G}$

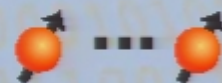
40



0000000000....,

$2^{40} = 1\text{T}$

50



0000000000....,

$2^{50} = 1\text{P}$

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



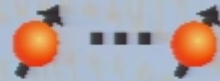
0000,0001,...,1111

$2^4 = 16$

⋮

⋮

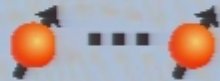
10



0000000000,...

$2^{10} = 1\text{k}$

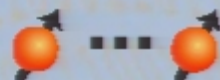
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0000000000....,

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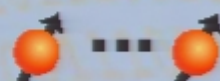
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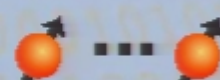
40



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Theory vs experiment



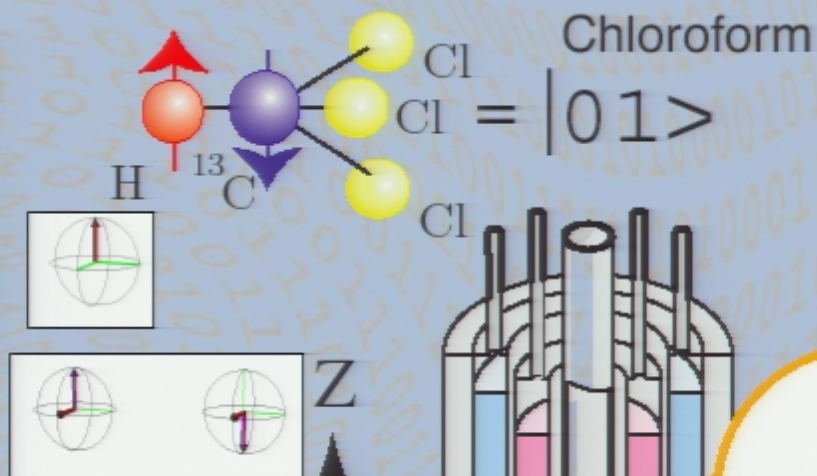
Nuclear Magnetic Resonance



Bloch



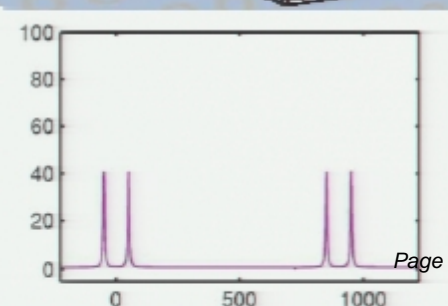
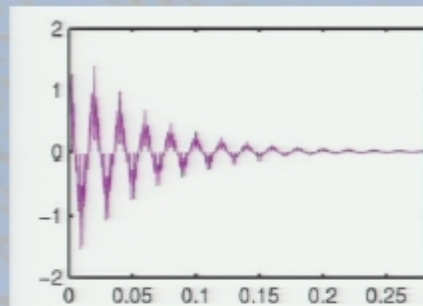
Purcell



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Bruker 700



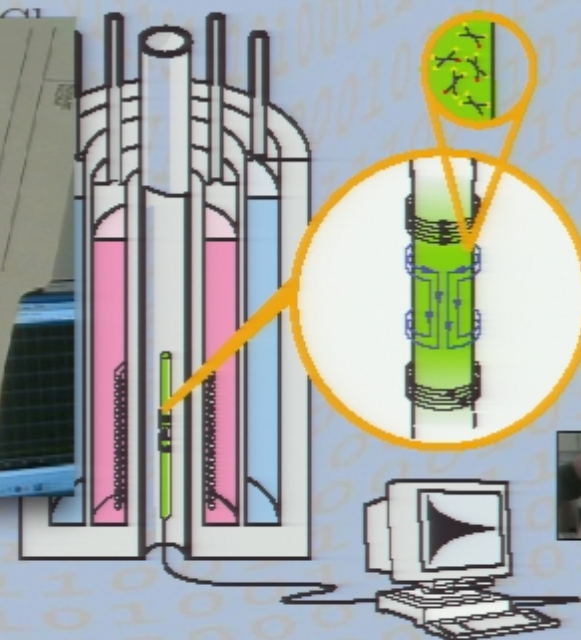
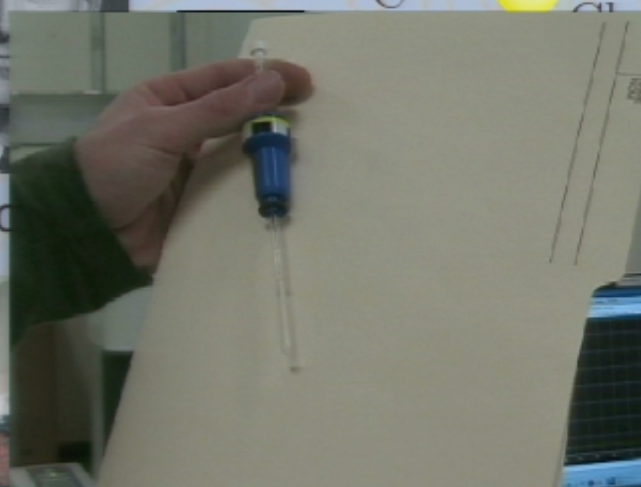
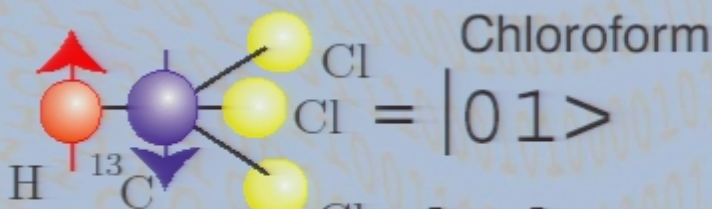
Nuclear Magnetic Resonance



Bloch



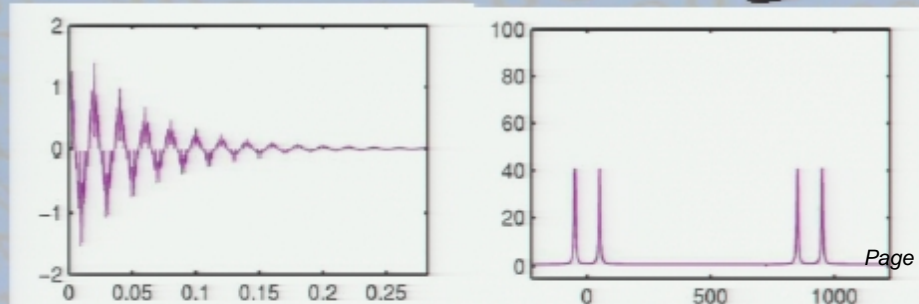
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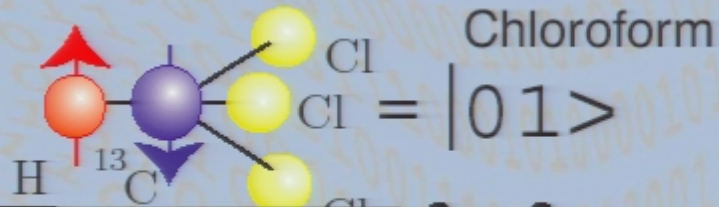
Nuclear Magnetic Resonance



Bloch



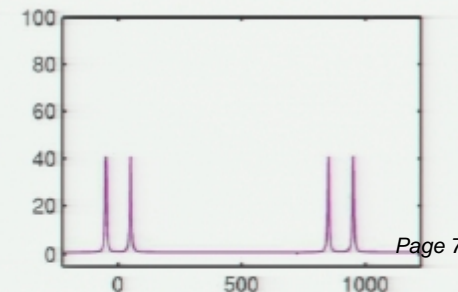
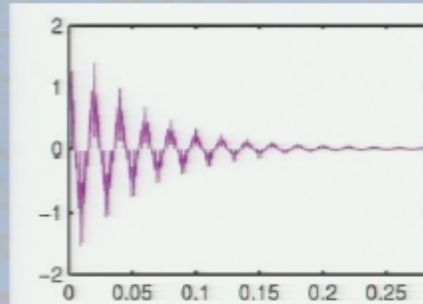
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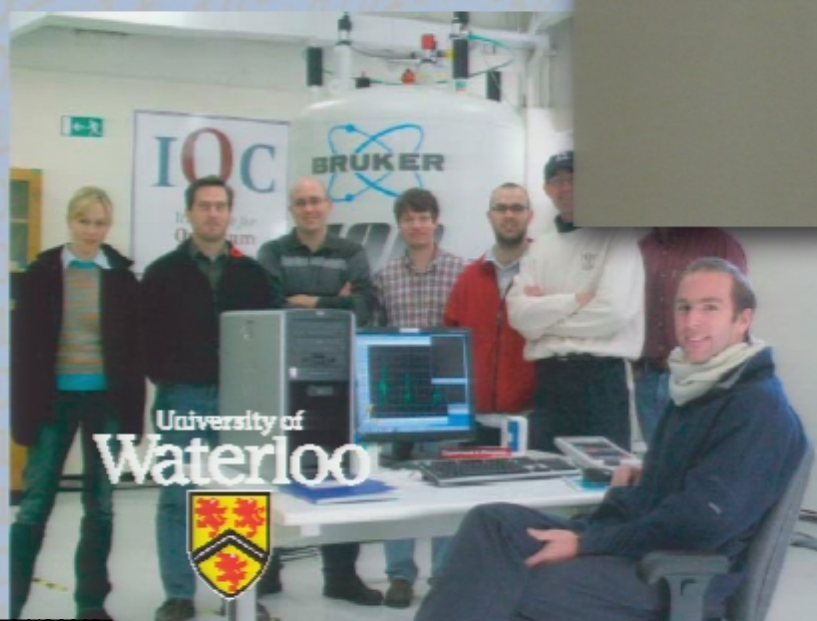
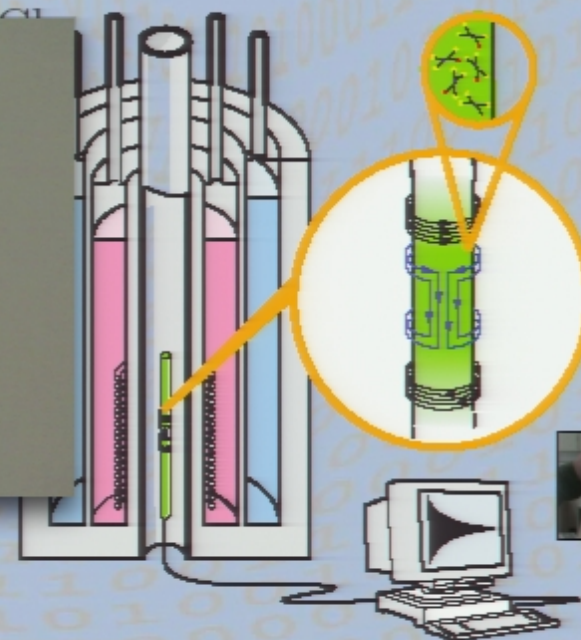
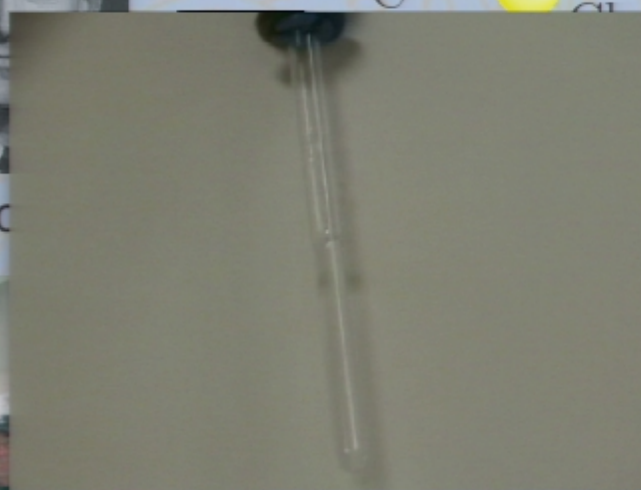
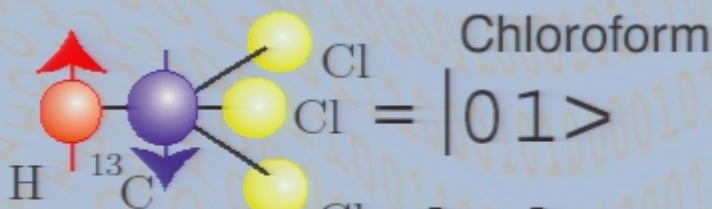
Nuclear Magnetic Resonance



Bloch



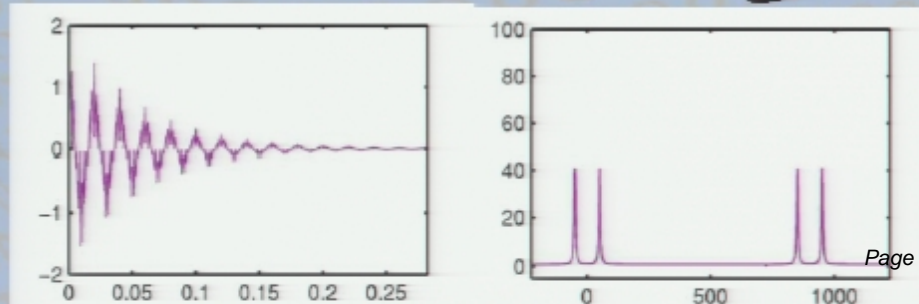
Purcell



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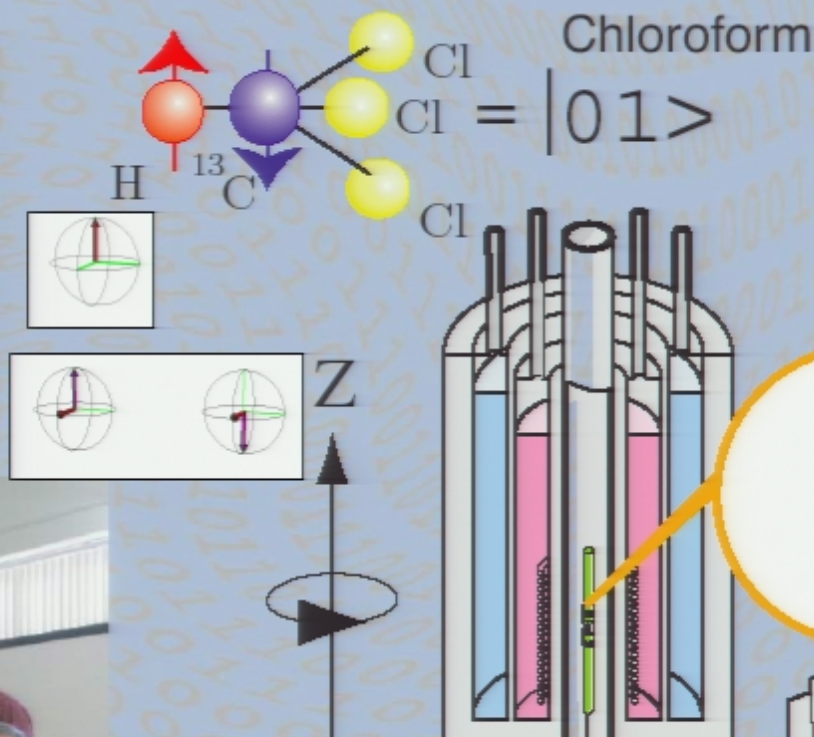
Nuclear Magnetic Resonance



Bloch



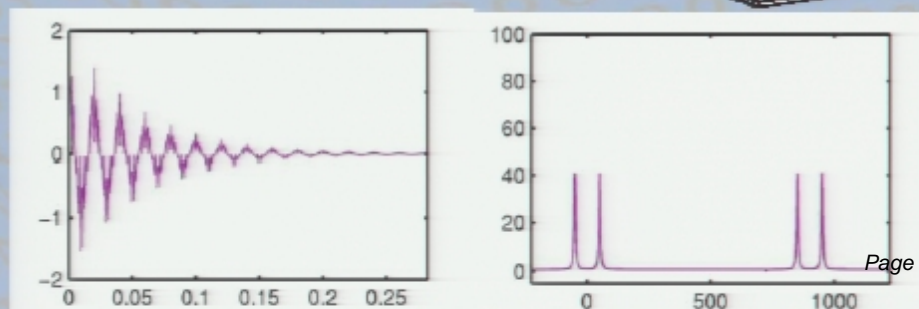
Purcell



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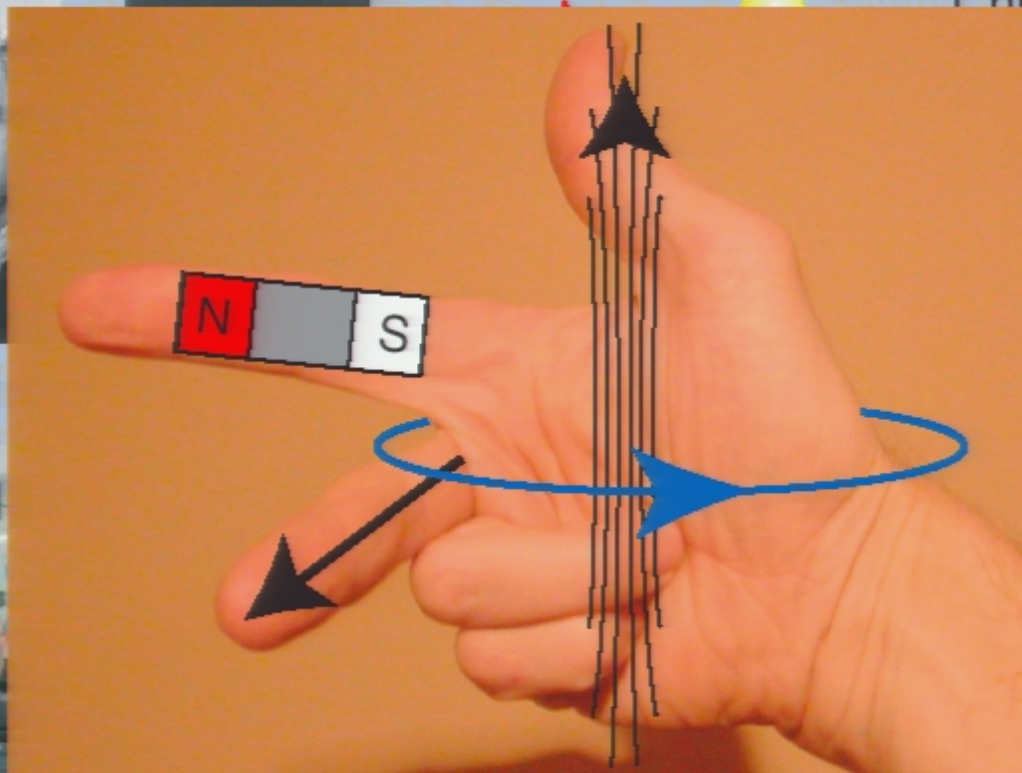
Bruker 700



Nuclear Magnetic Resonance



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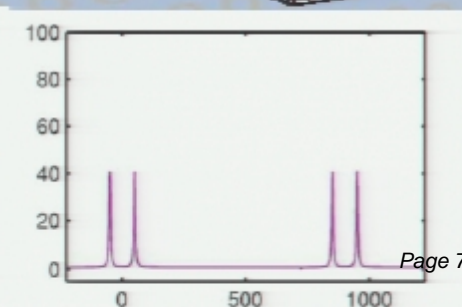
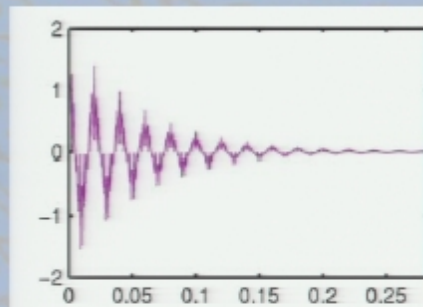
Chloroform



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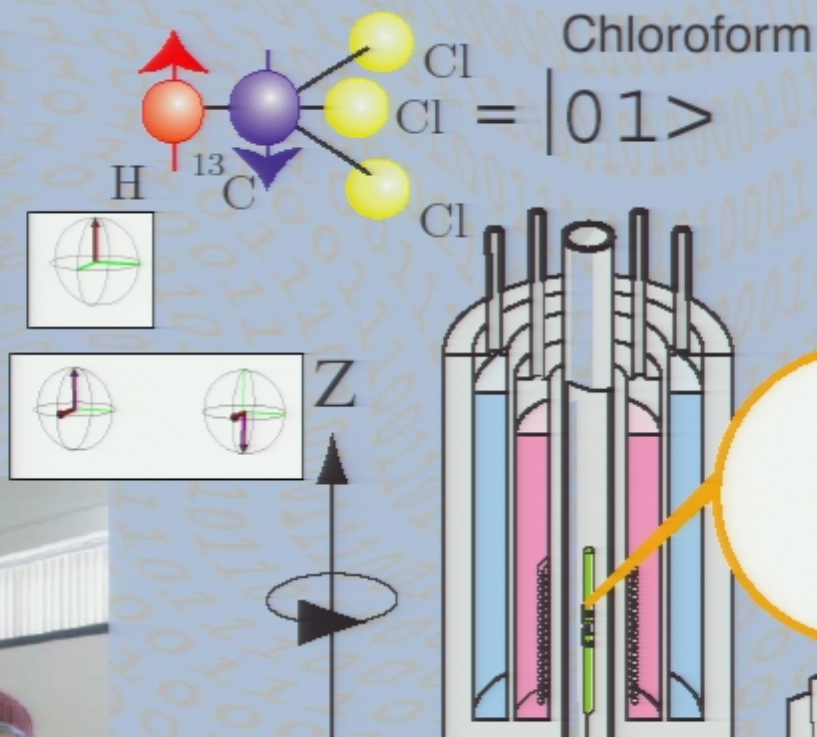
Nuclear Magnetic Resonance



Bloch



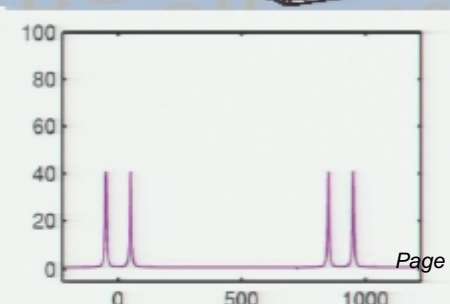
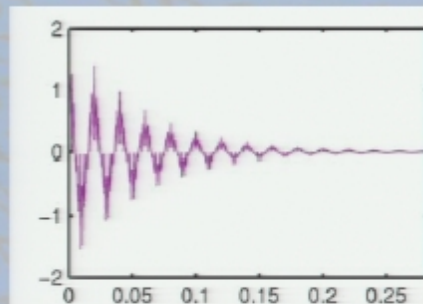
Purcell



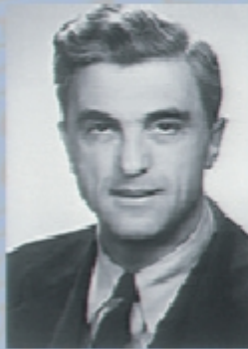
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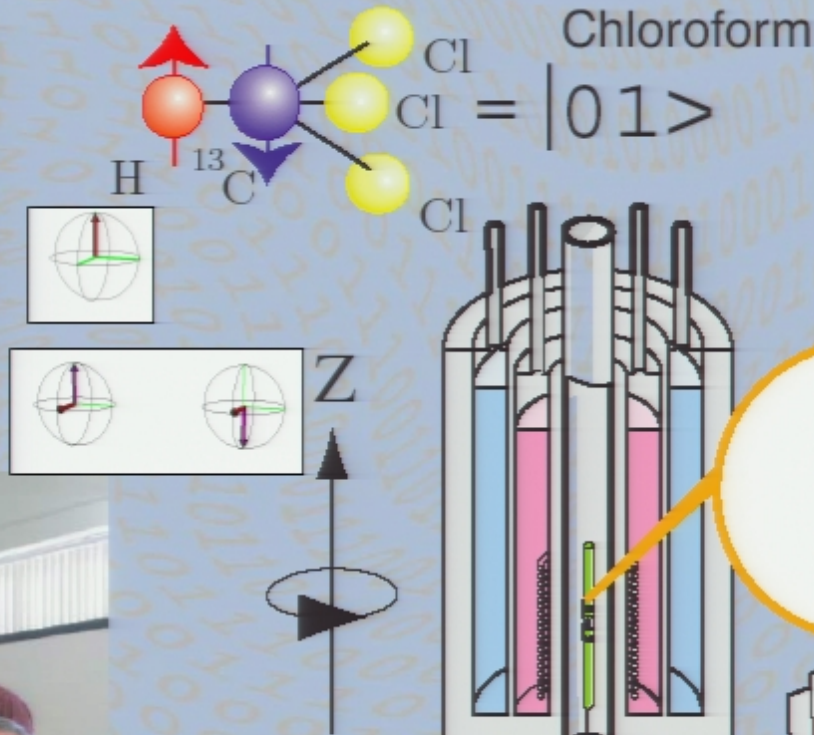
Nuclear Magnetic Resonance



Bloch



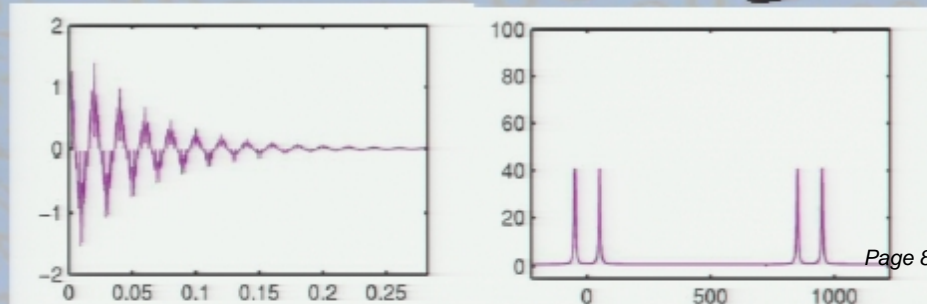
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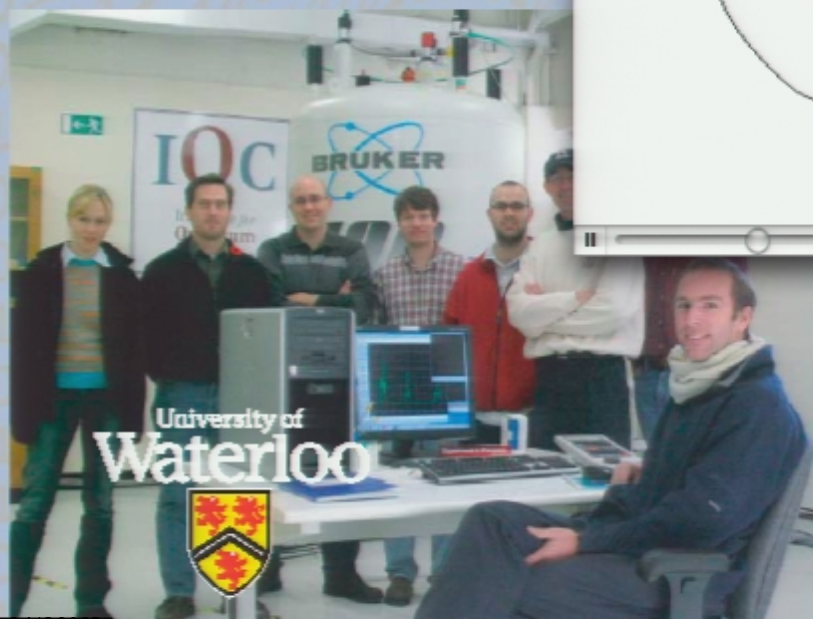
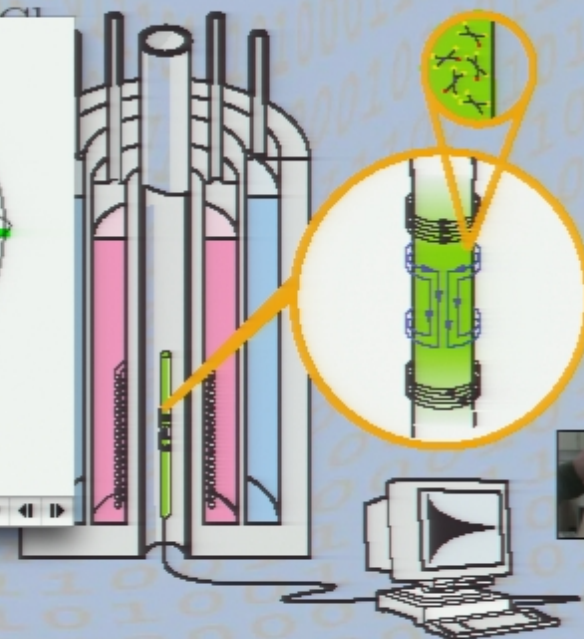
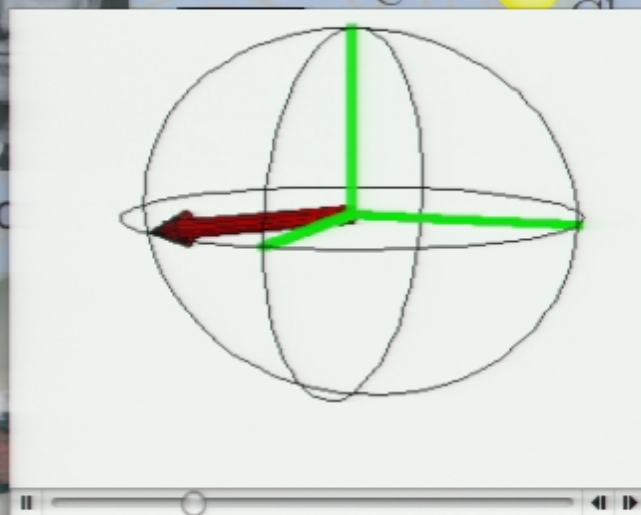
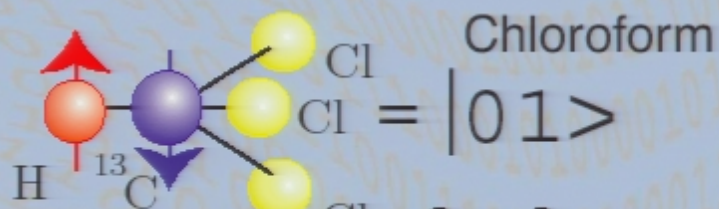
Nuclear Magnetic Resonance



Bloch



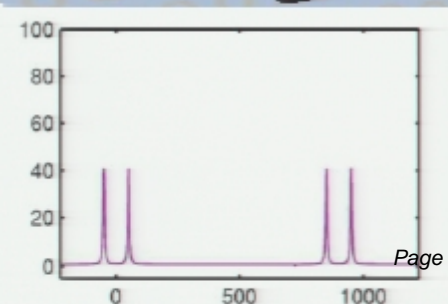
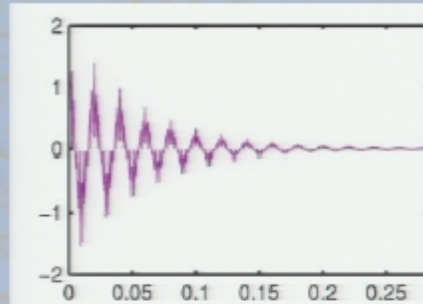
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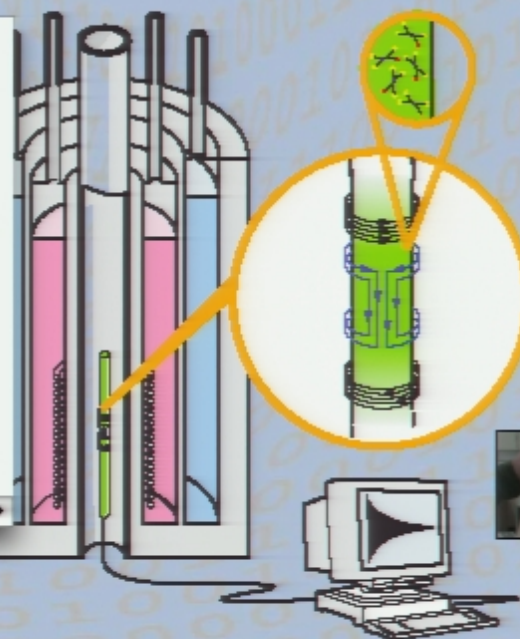
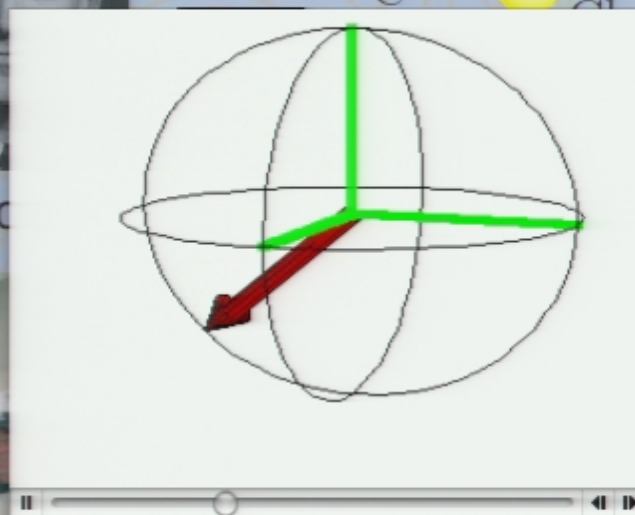
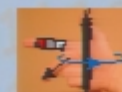
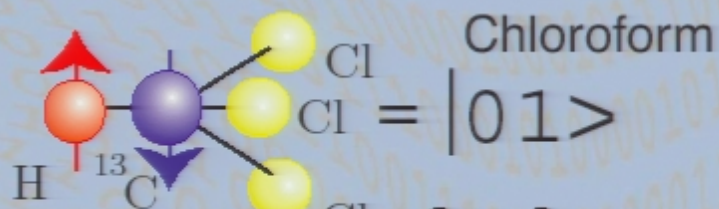
Nuclear Magnetic Resonance



Bloch



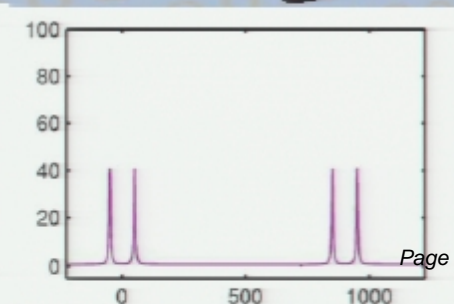
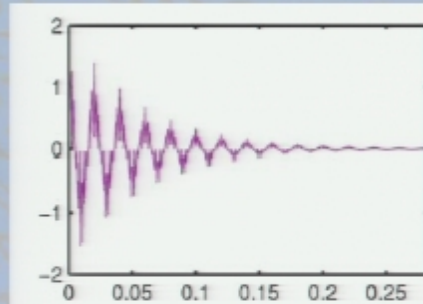
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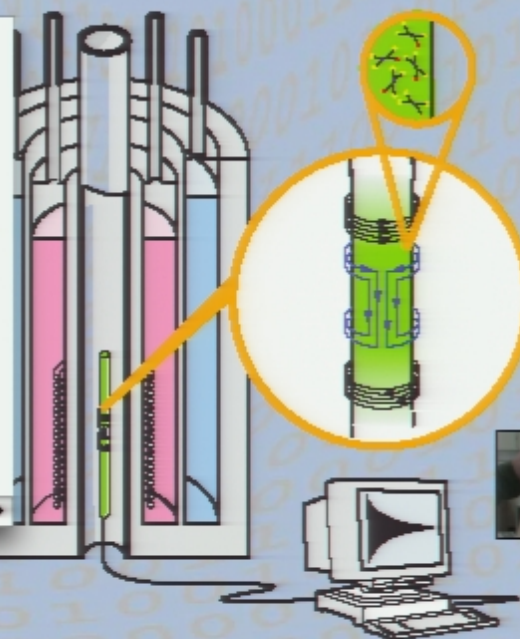
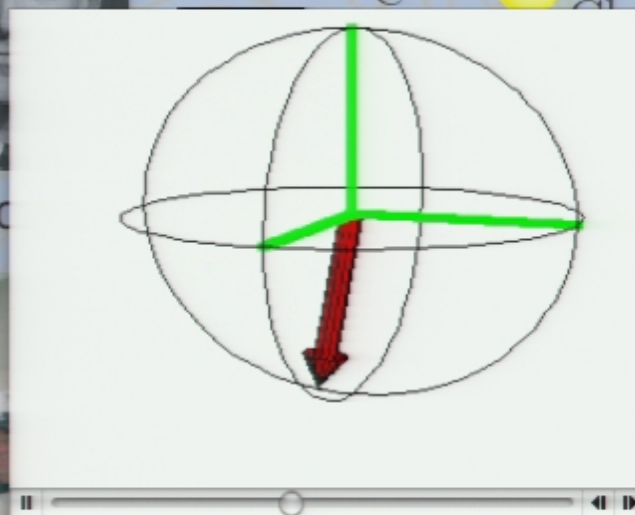
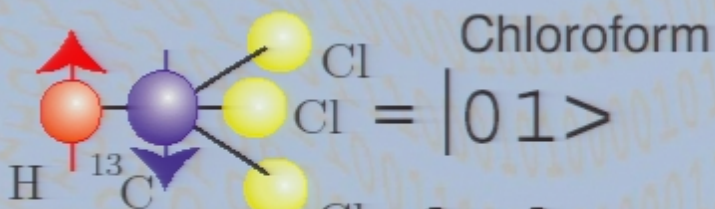
Nuclear Magnetic Resonance



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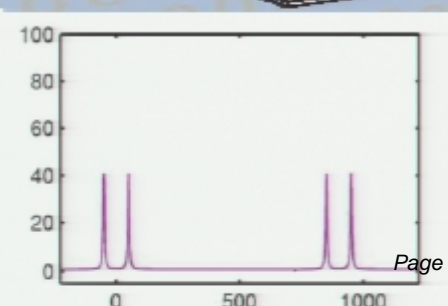
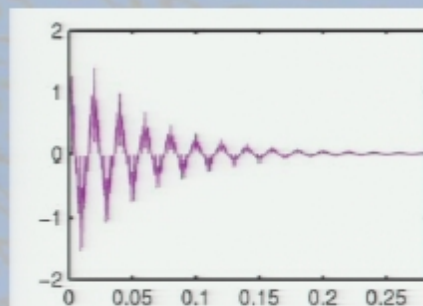
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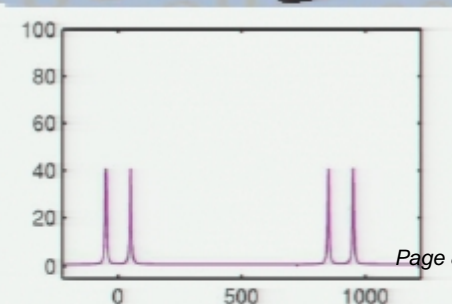
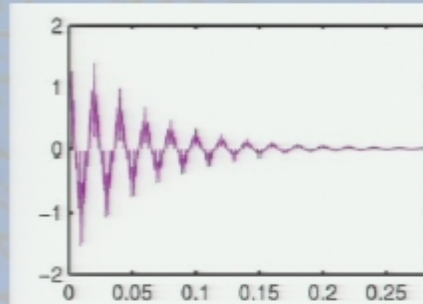
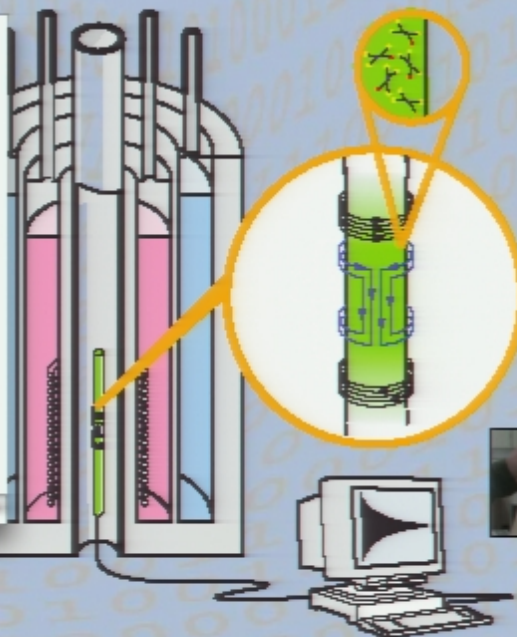
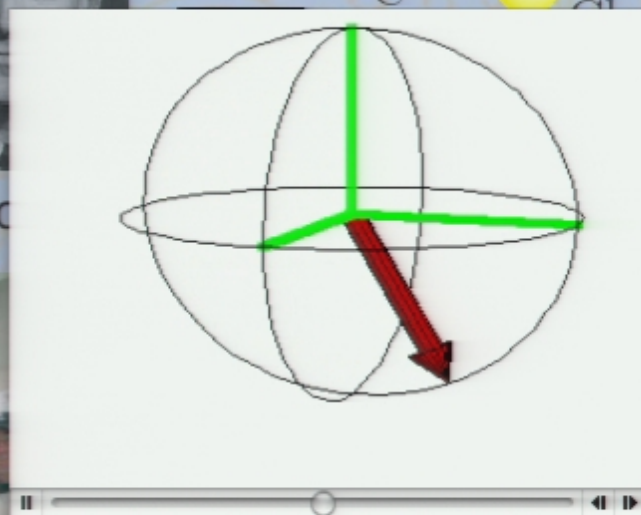
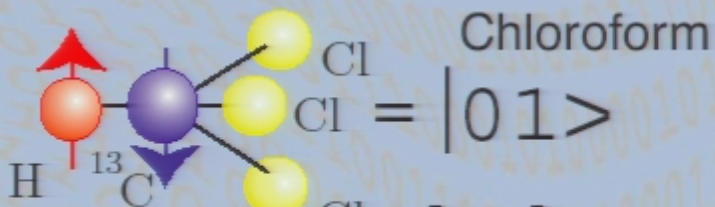
Nuclear Magnetic Resonance



Bloch



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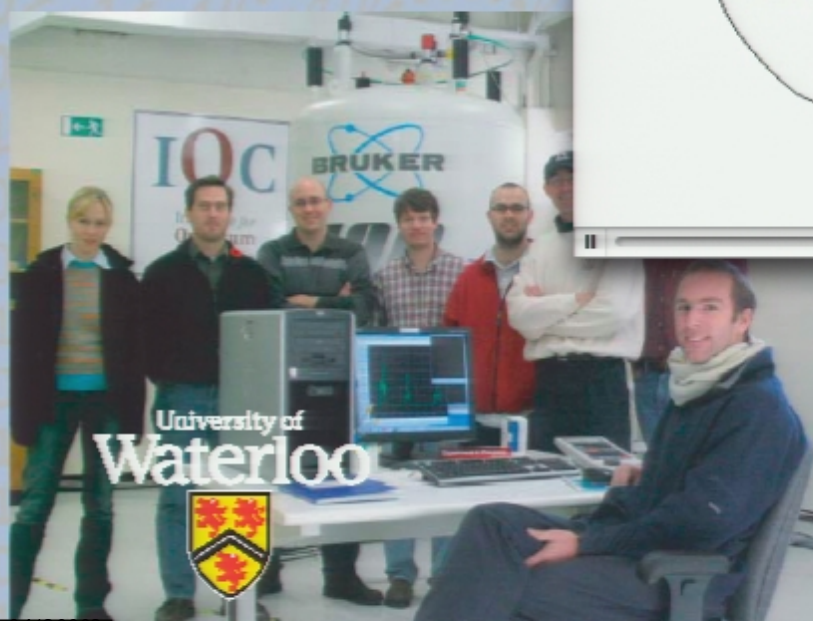
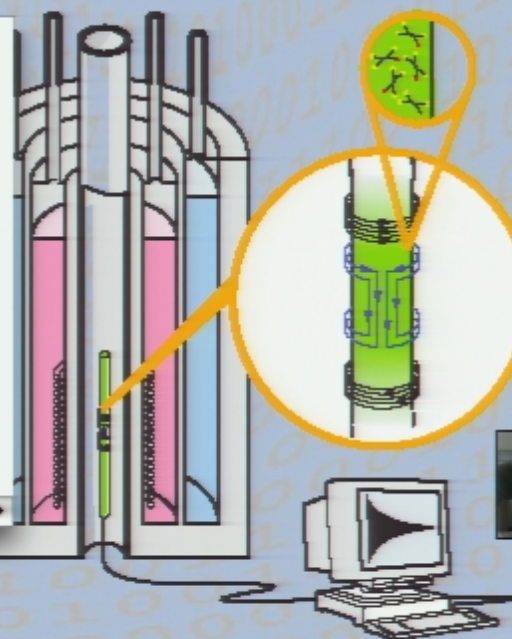
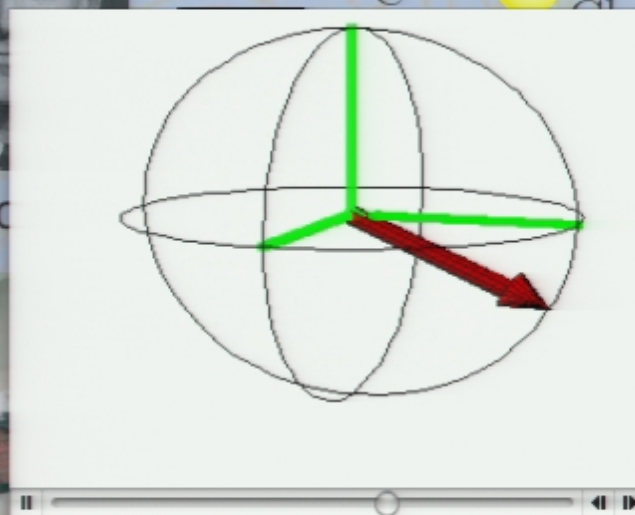
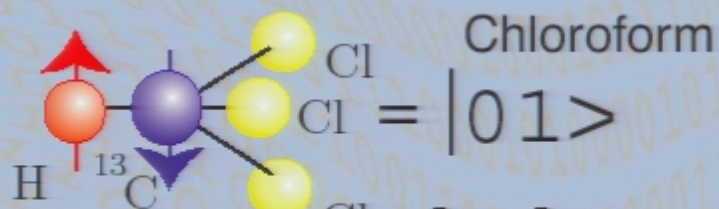
Nuclear Magnetic Resonance



Bloch



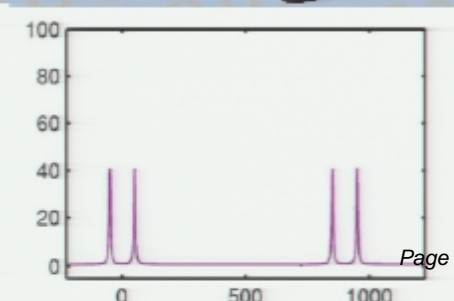
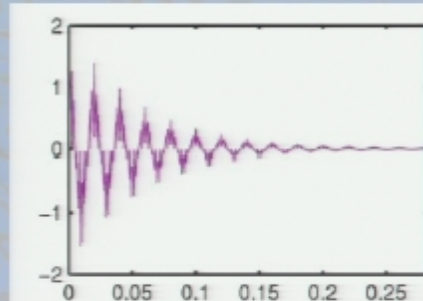
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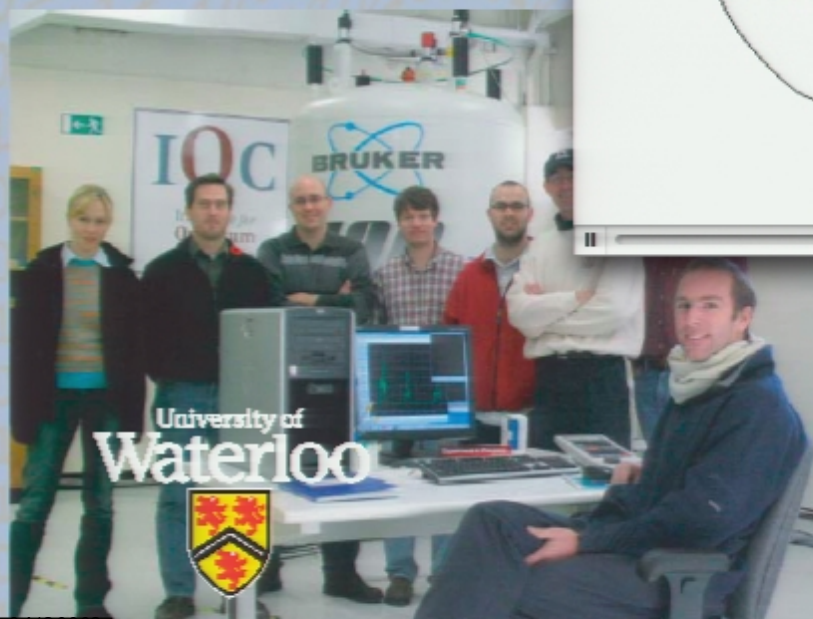
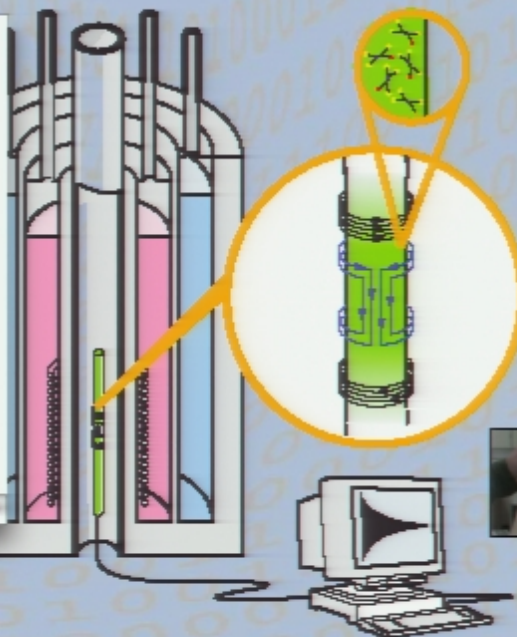
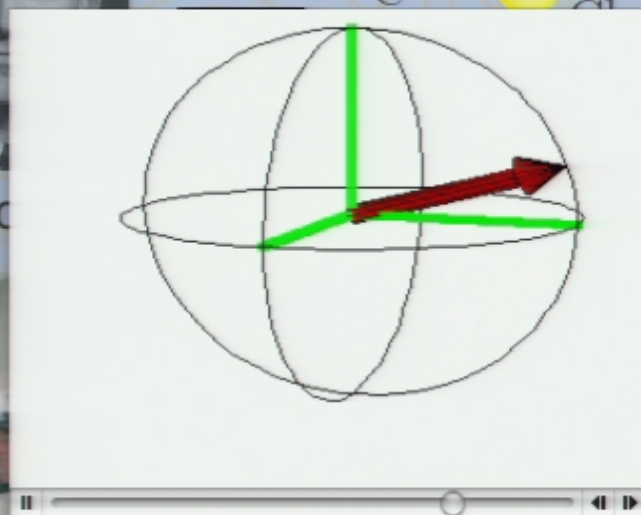
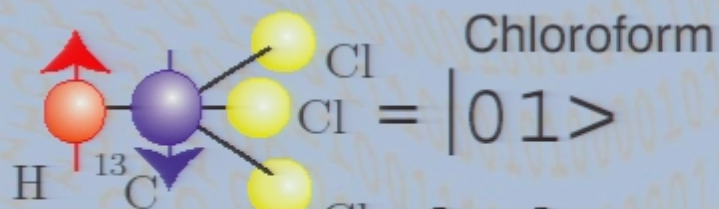
Nuclear Magnetic Resonance



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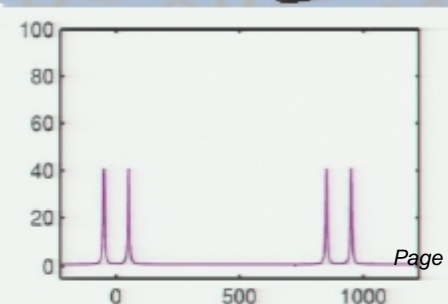
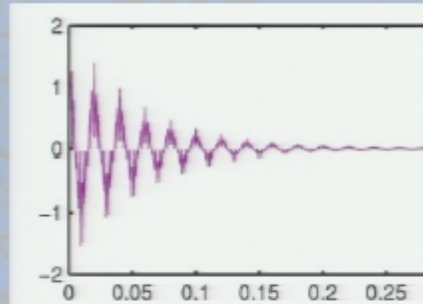
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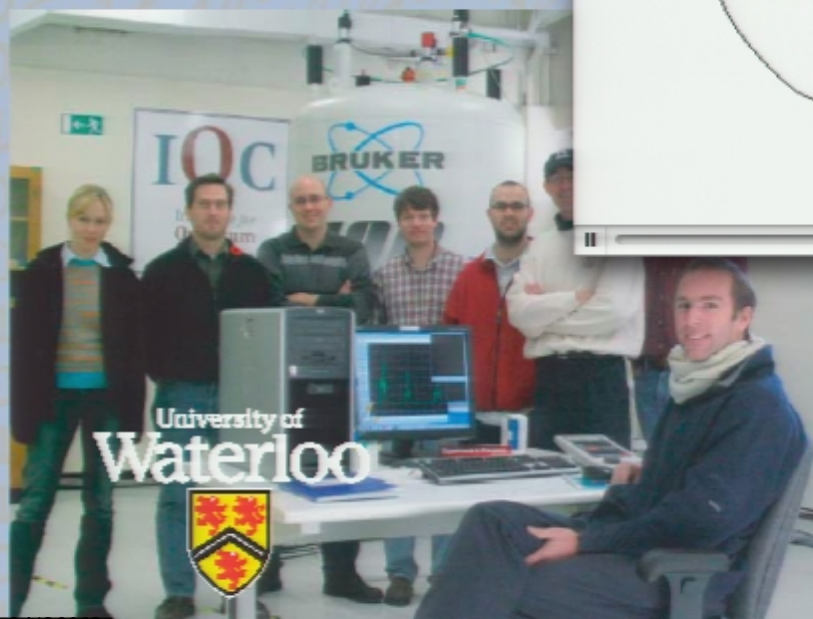
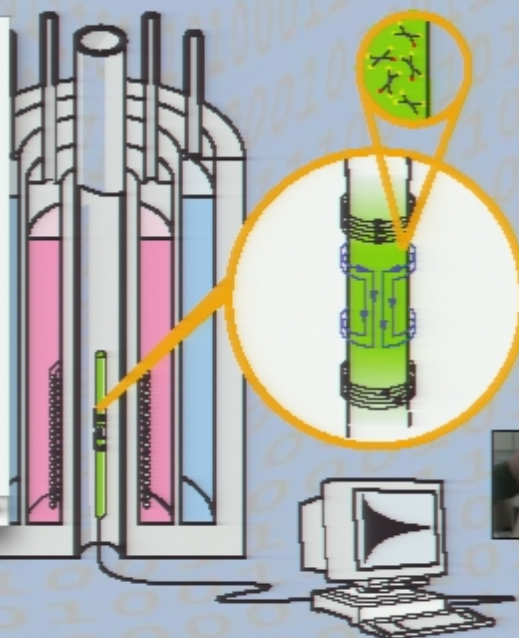
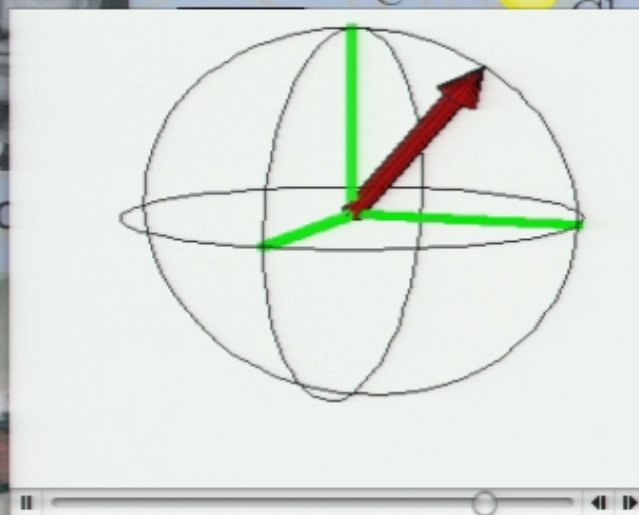
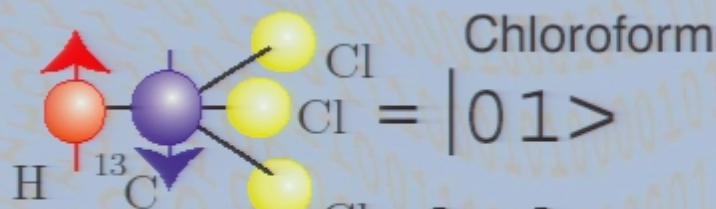
Nuclear Magnetic Resonance



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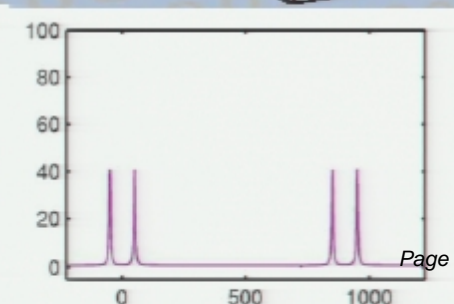
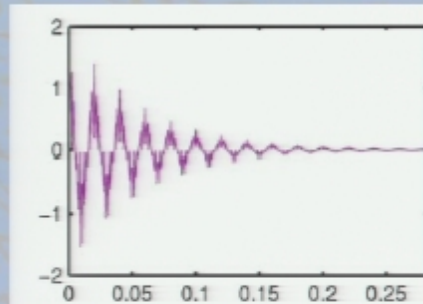
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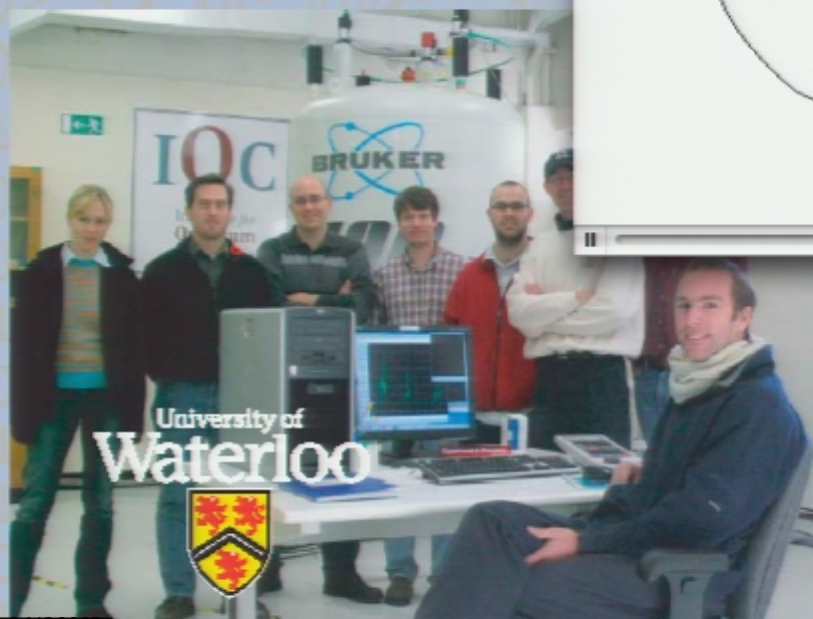
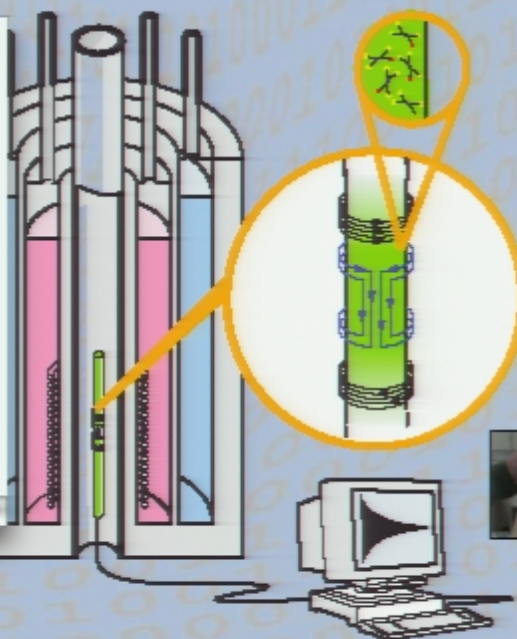
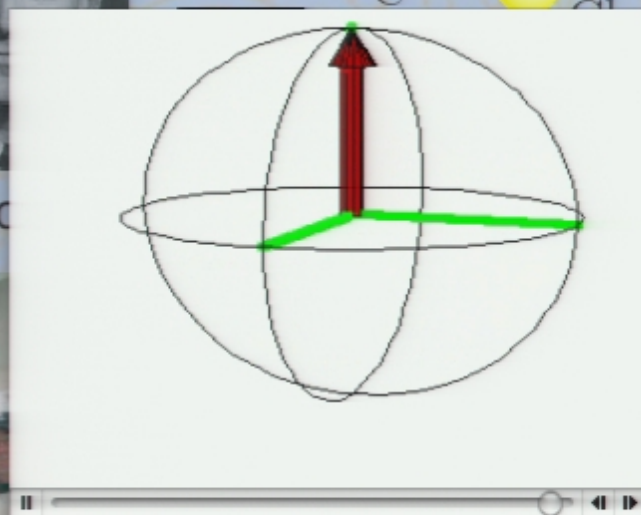
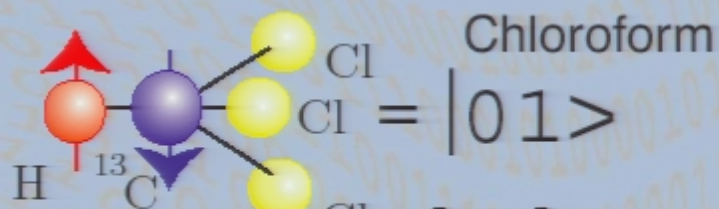
Nuclear Magnetic Resonance



Bloch



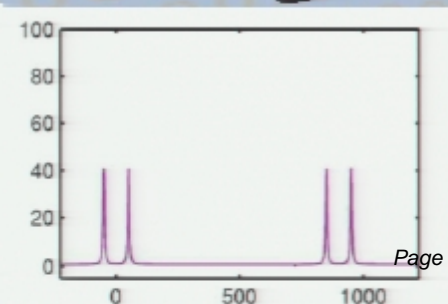
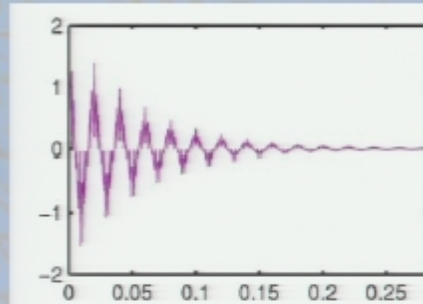
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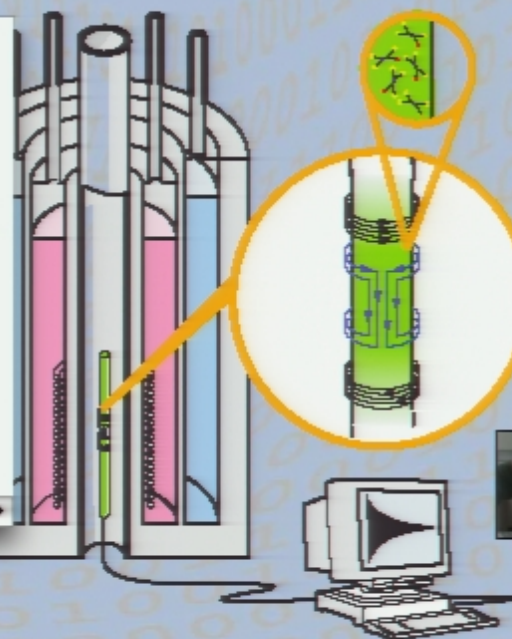
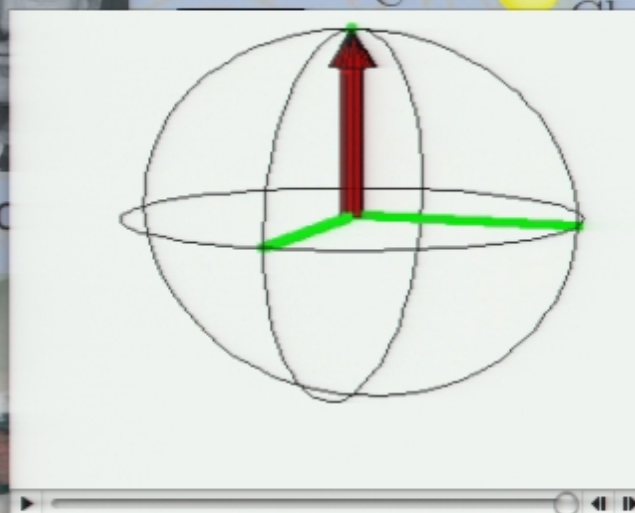
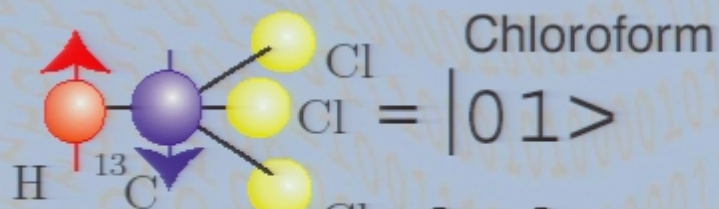
Nuclear Magnetic Resonance



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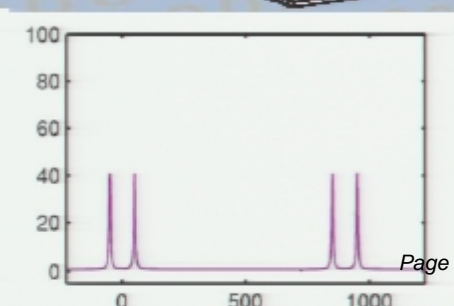
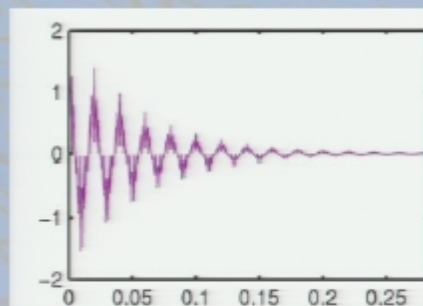
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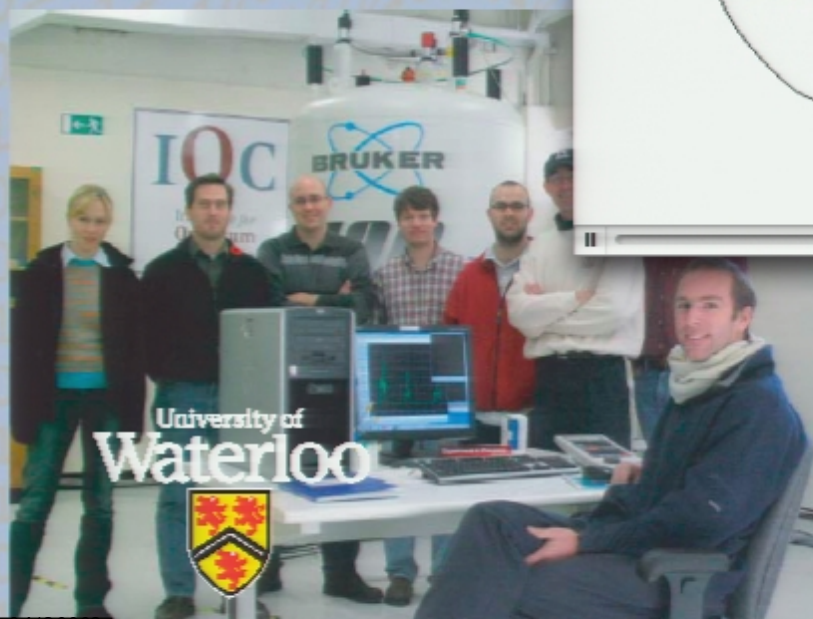
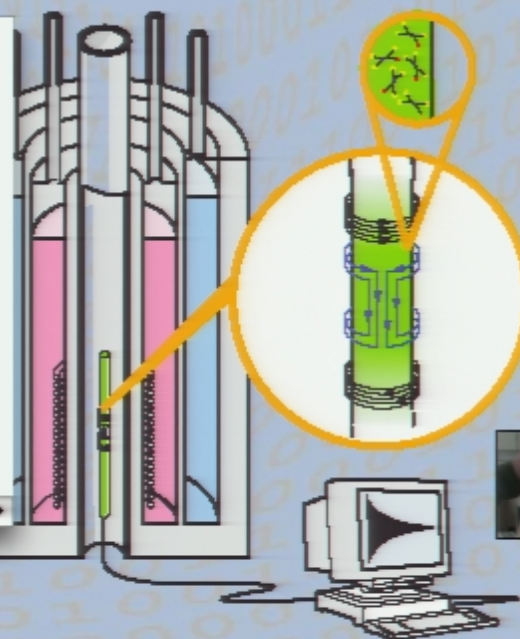
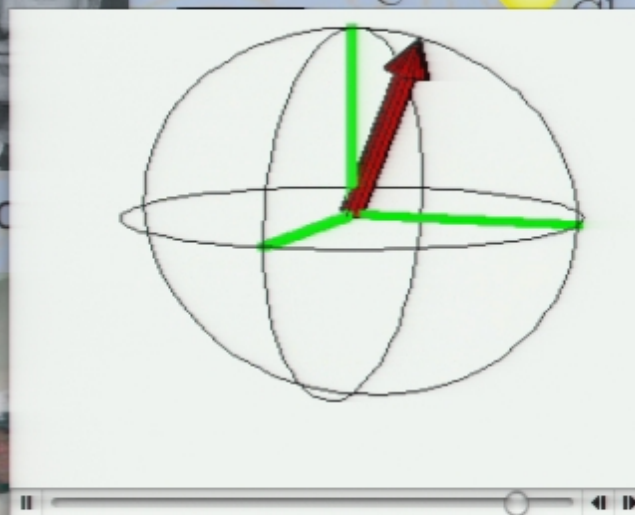
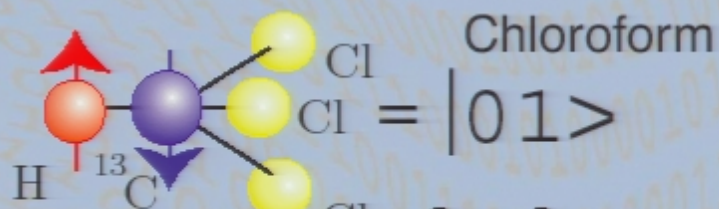
Nuclear Magnetic Resonance



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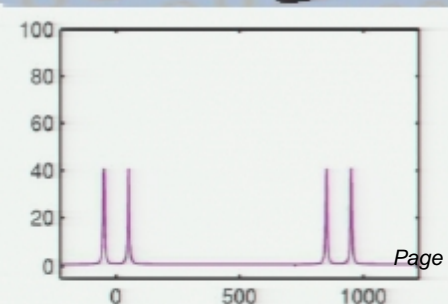
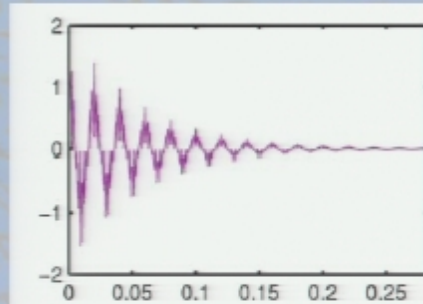
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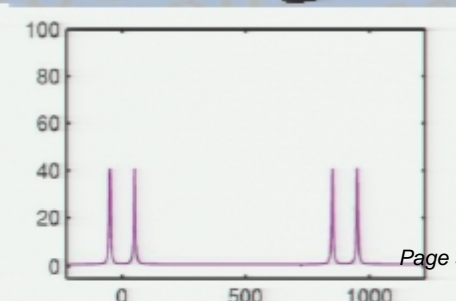
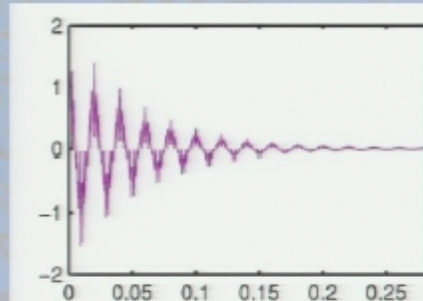
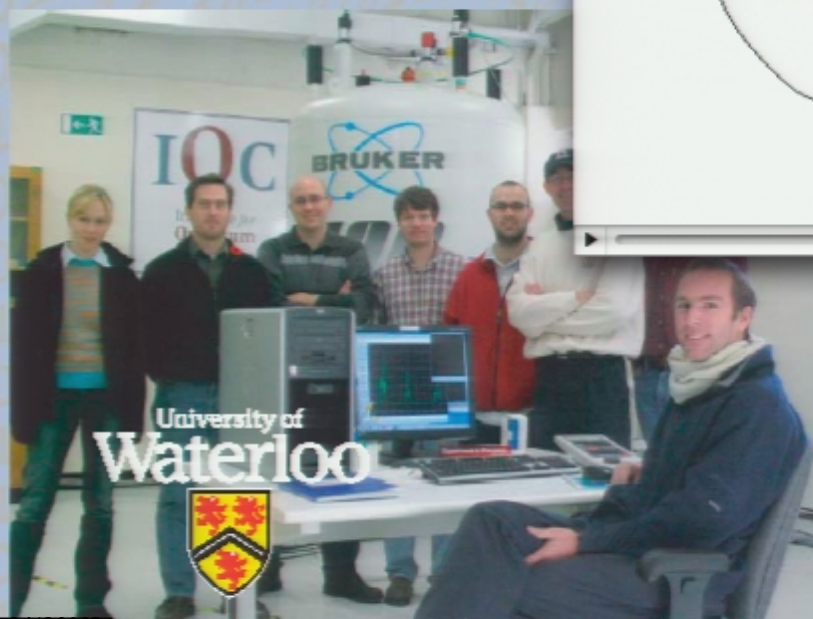
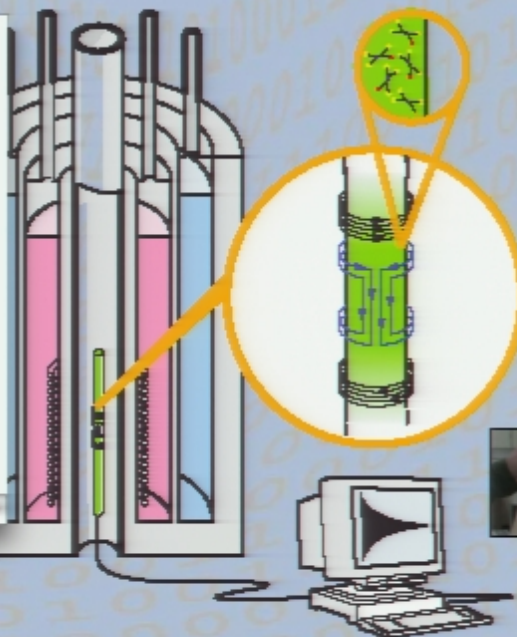
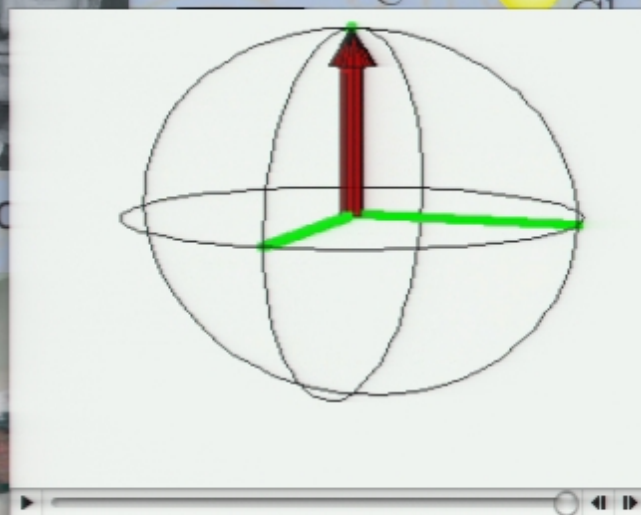
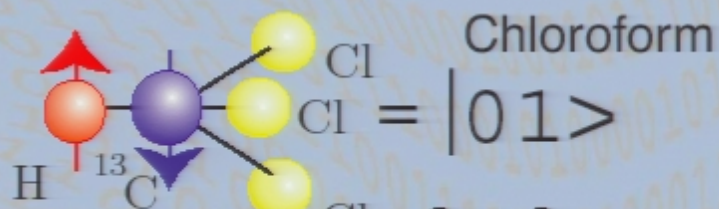
Nuclear Magnetic Resonance



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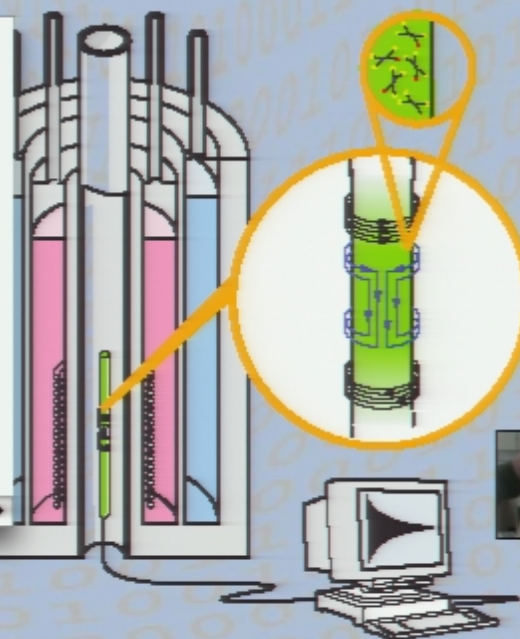
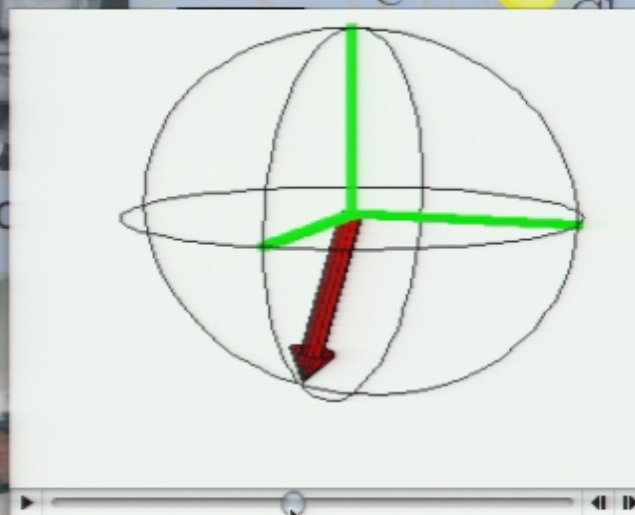
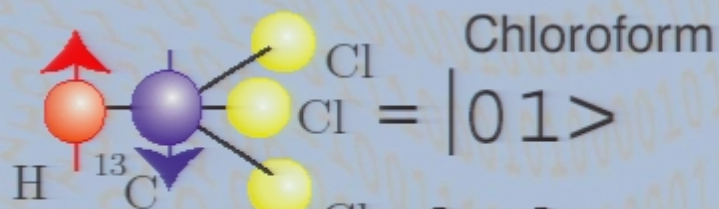
Nuclear Magnetic Resonance



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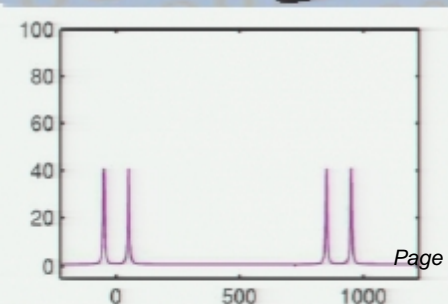
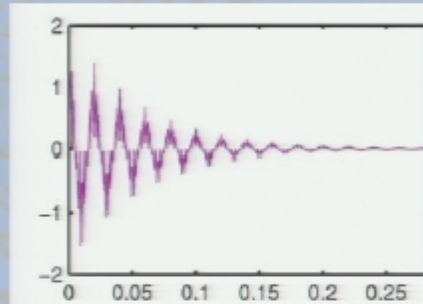
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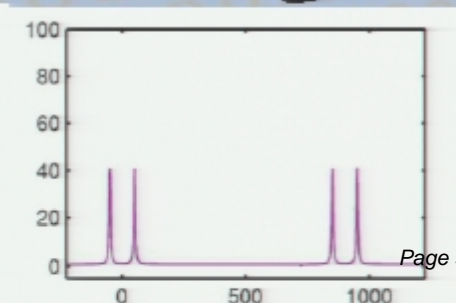
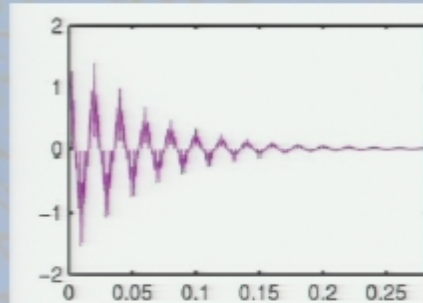
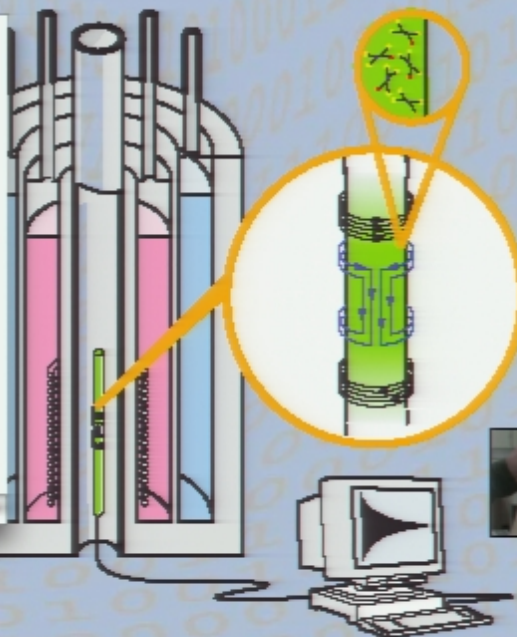
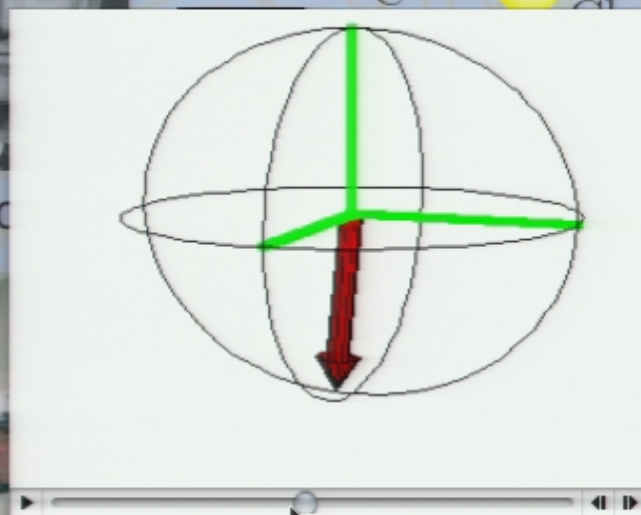
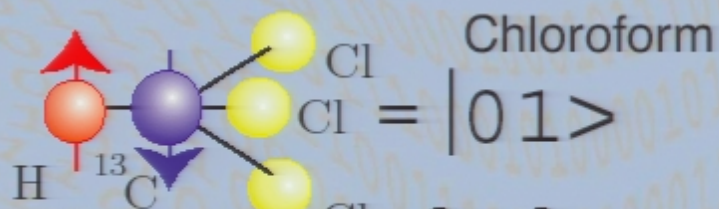
Nuclear Magnetic Resonance



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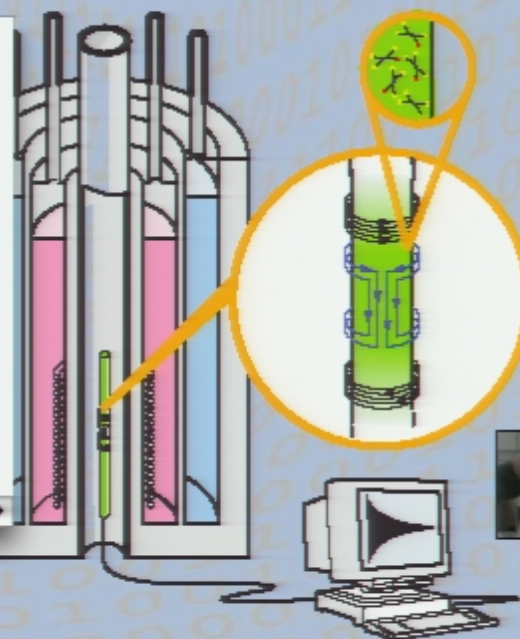
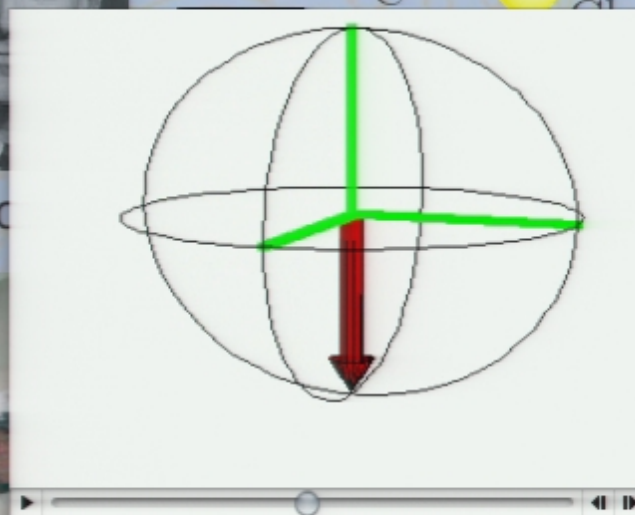
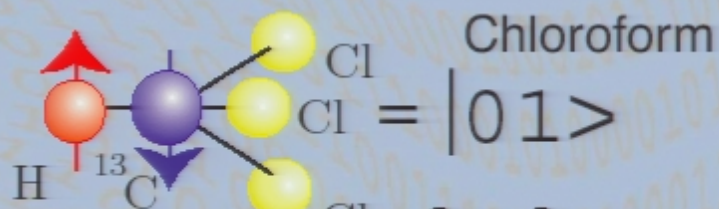
Nuclear Magnetic Resonance



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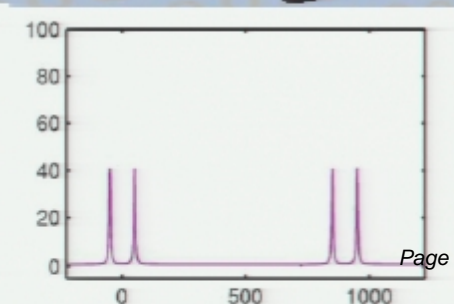
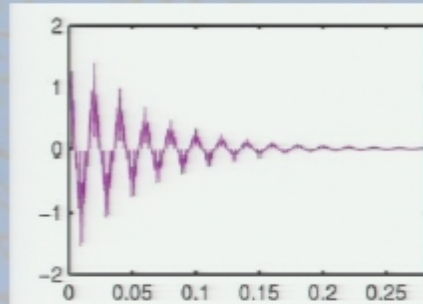
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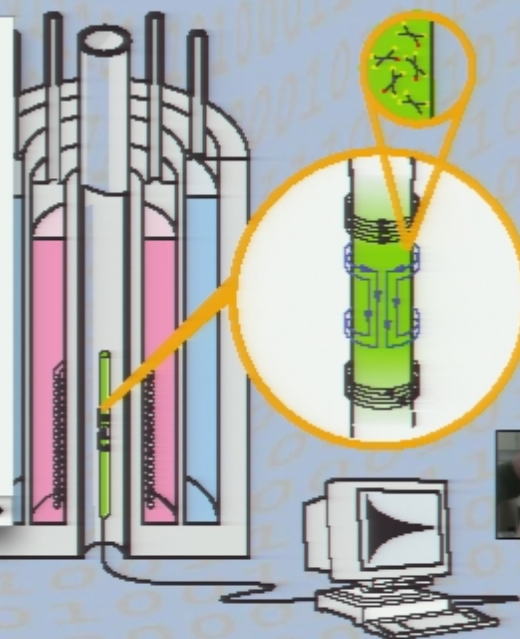
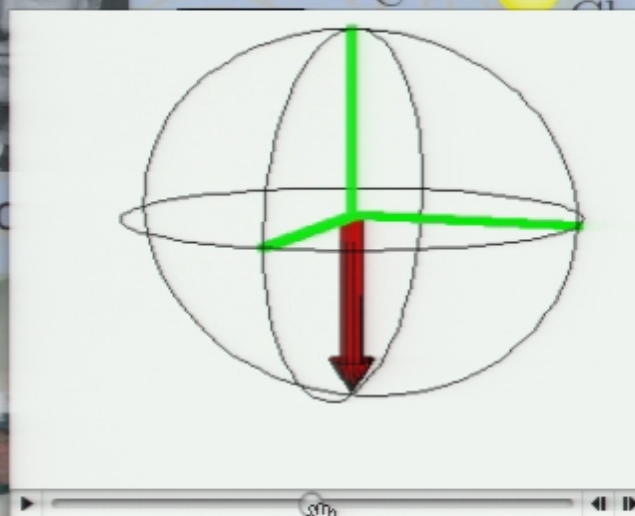
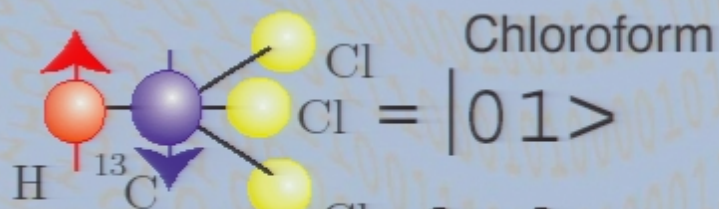
Nuclear Magnetic Resonance



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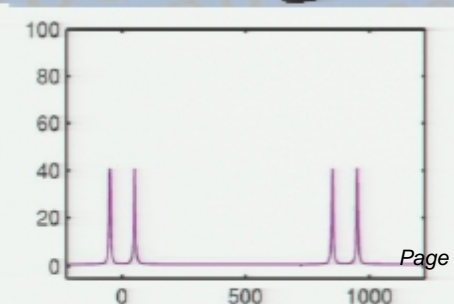
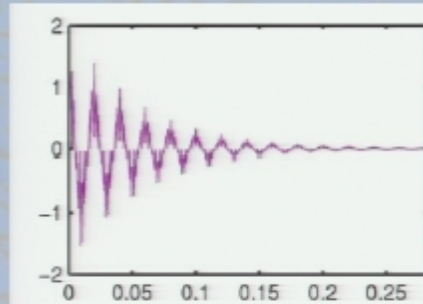
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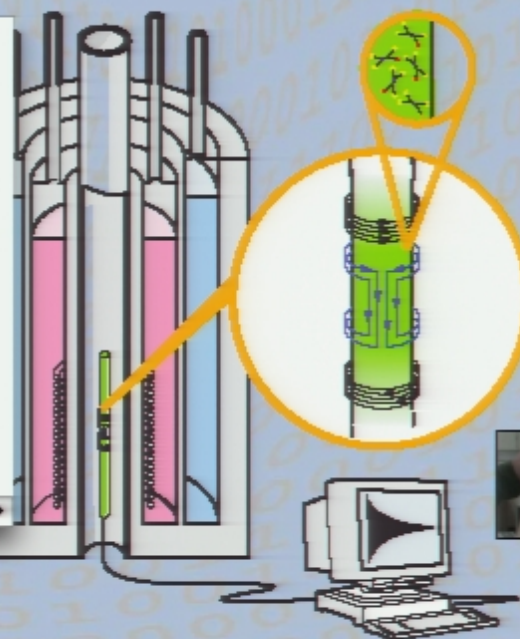
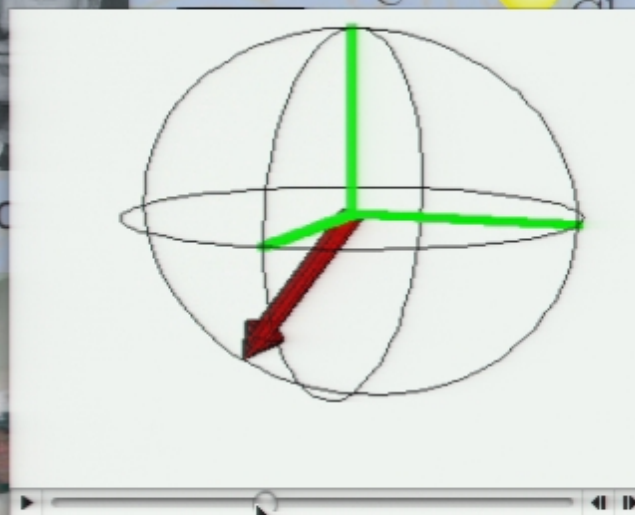
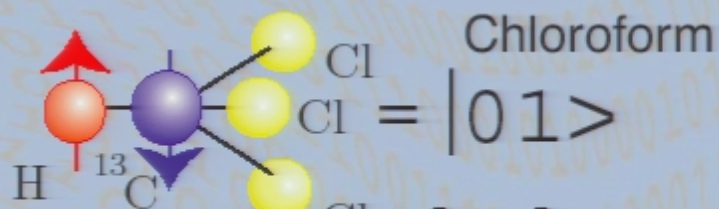
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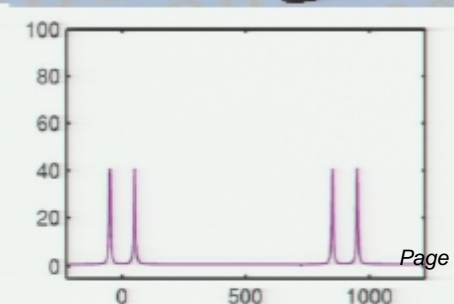
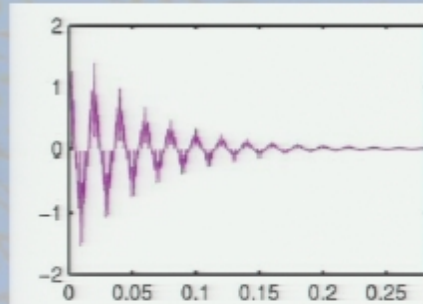
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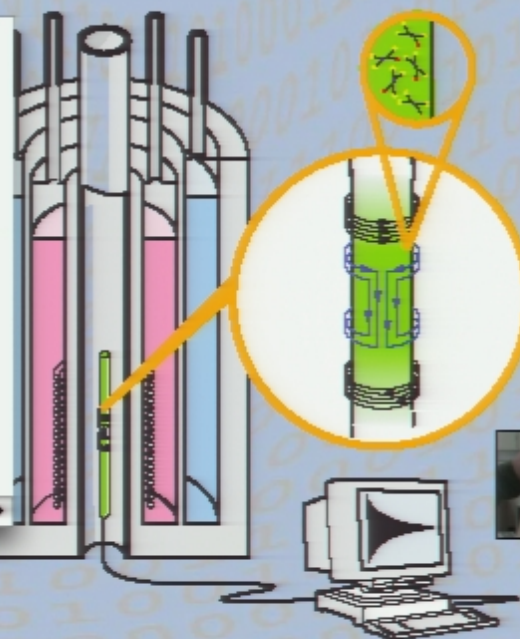
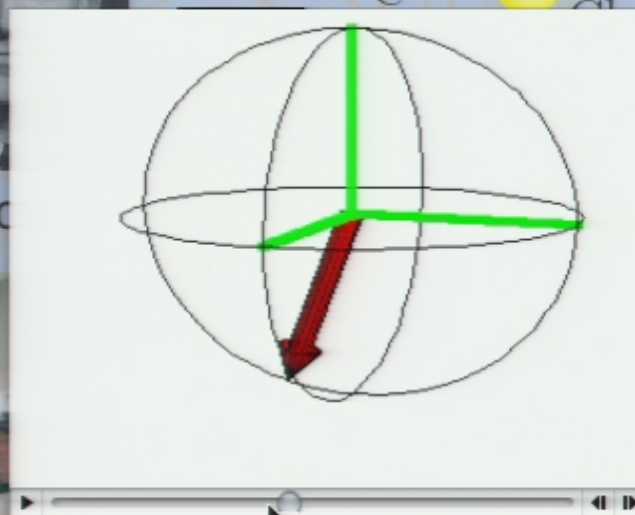
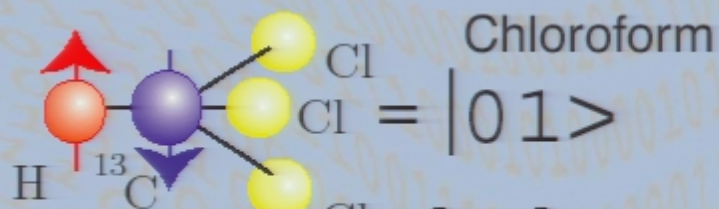
Nuclear Magnetic Resonance



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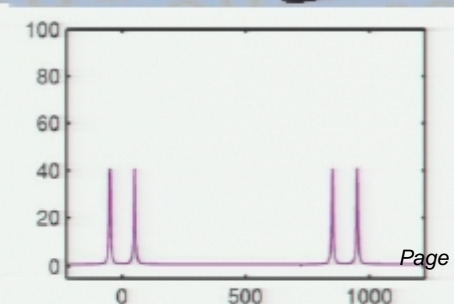
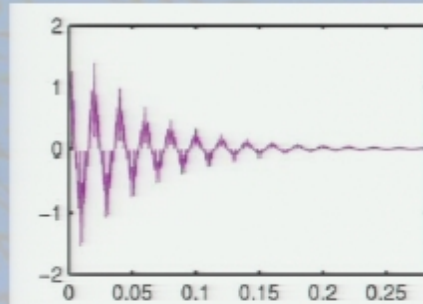
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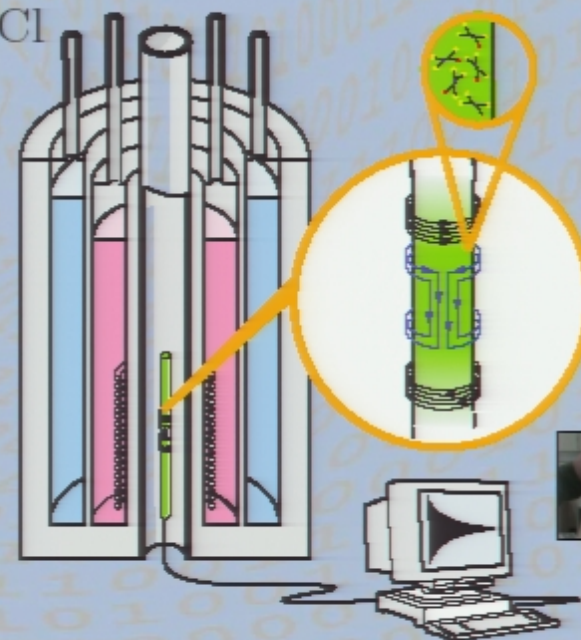
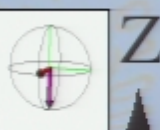
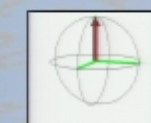
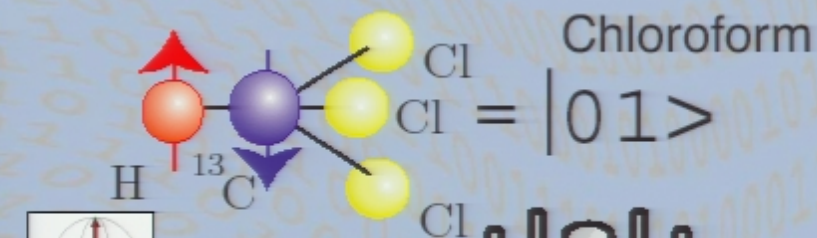
Nuclear Magnetic Resonance



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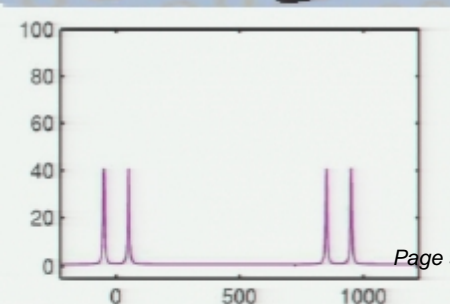
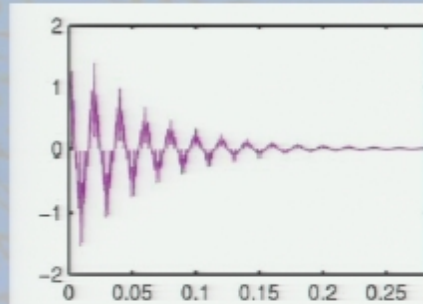
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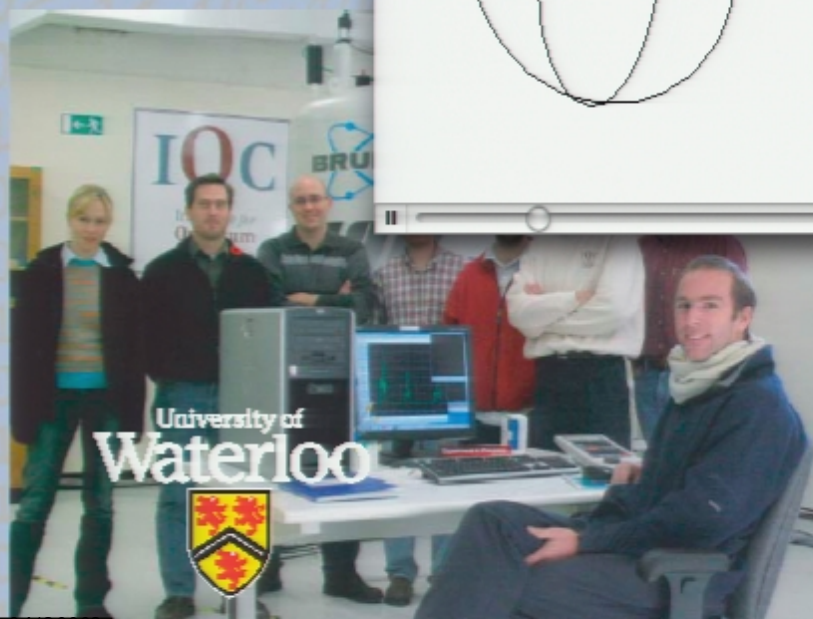
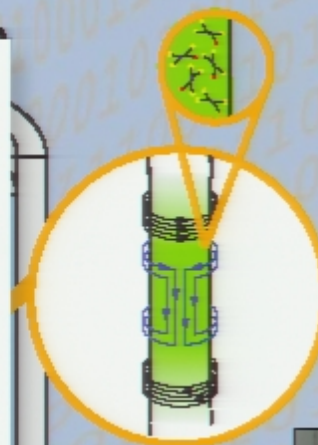
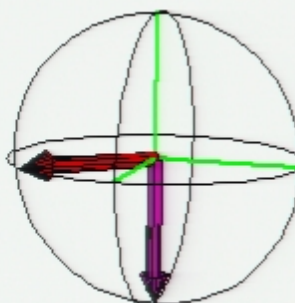
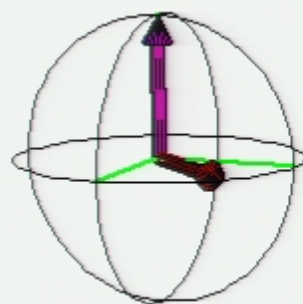
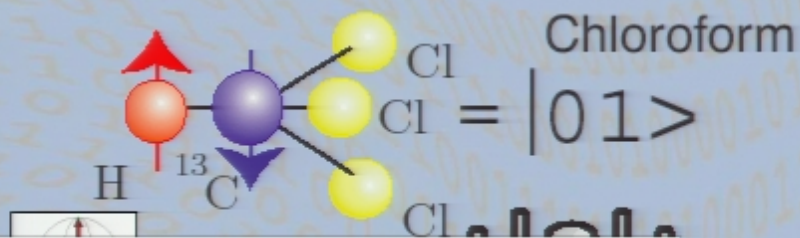
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Nuclear Magnetic Resonance



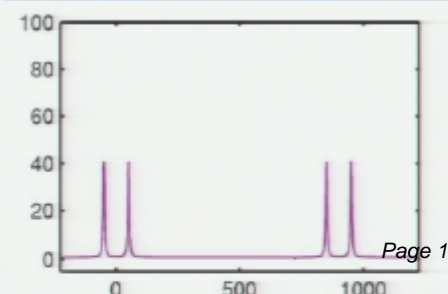
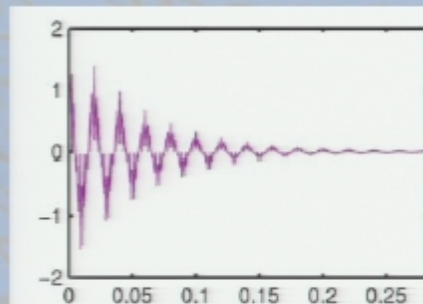
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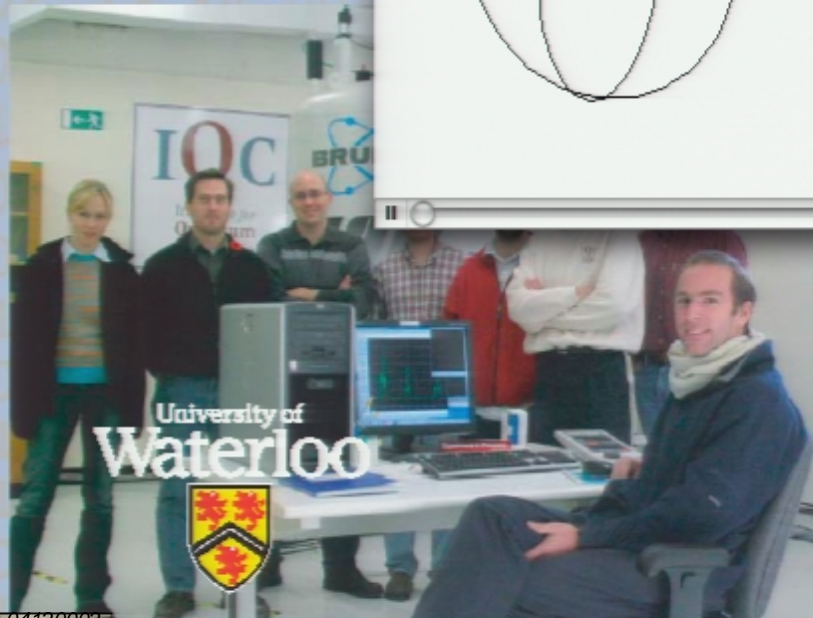
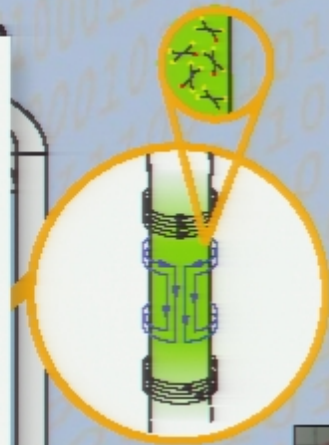
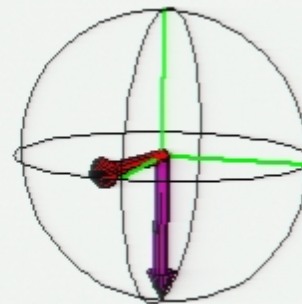
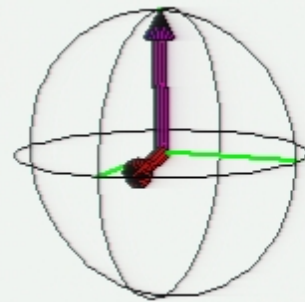
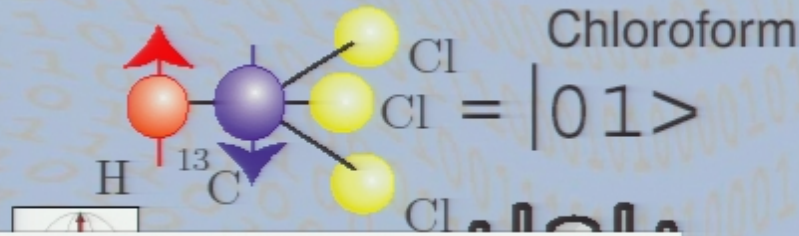
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Nuclear Magnetic Resonance



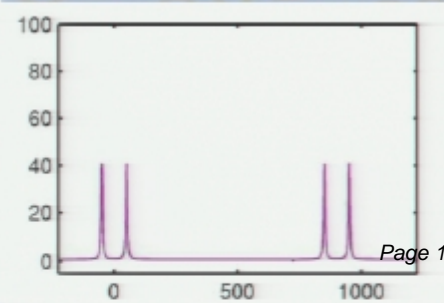
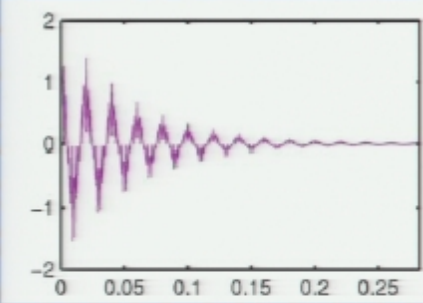
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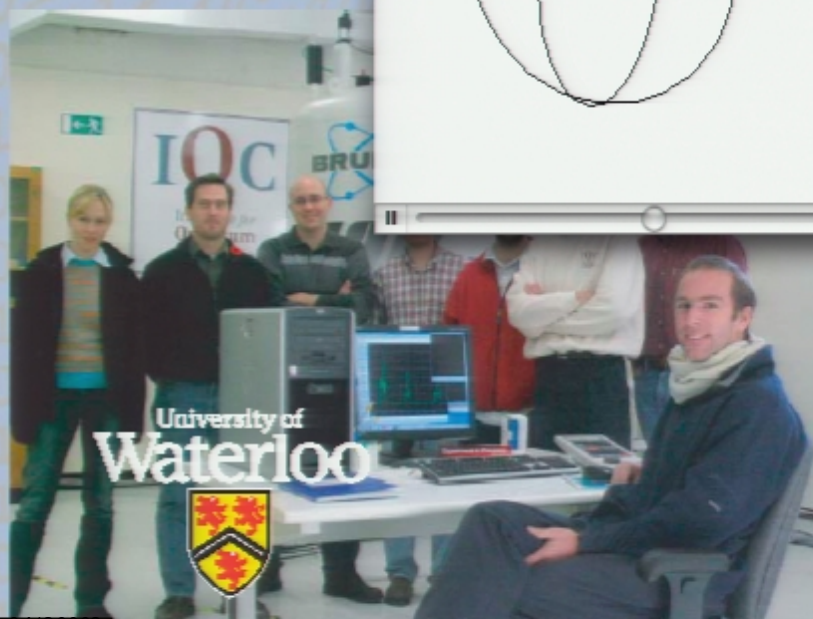
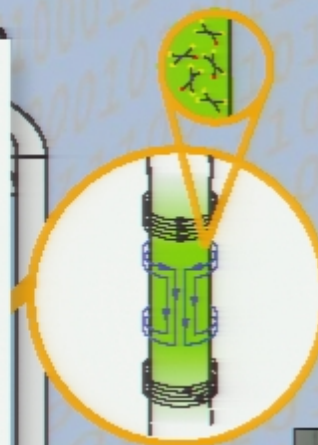
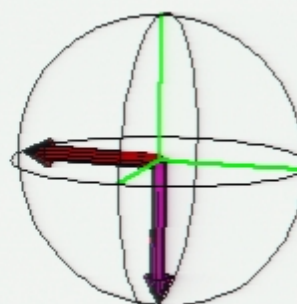
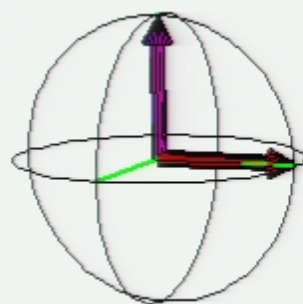
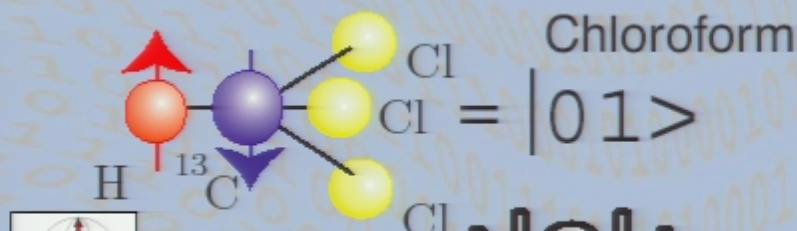
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Nuclear Magnetic Resonance



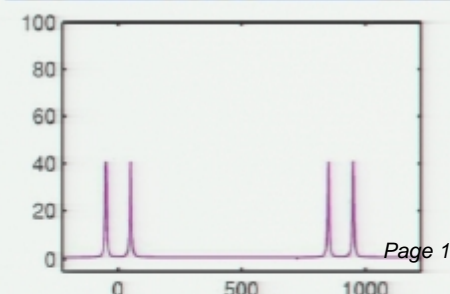
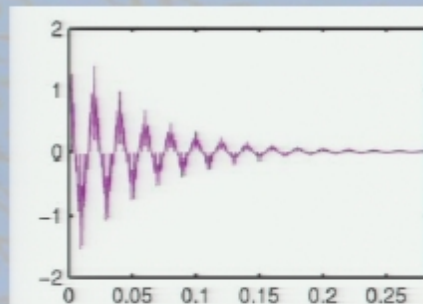
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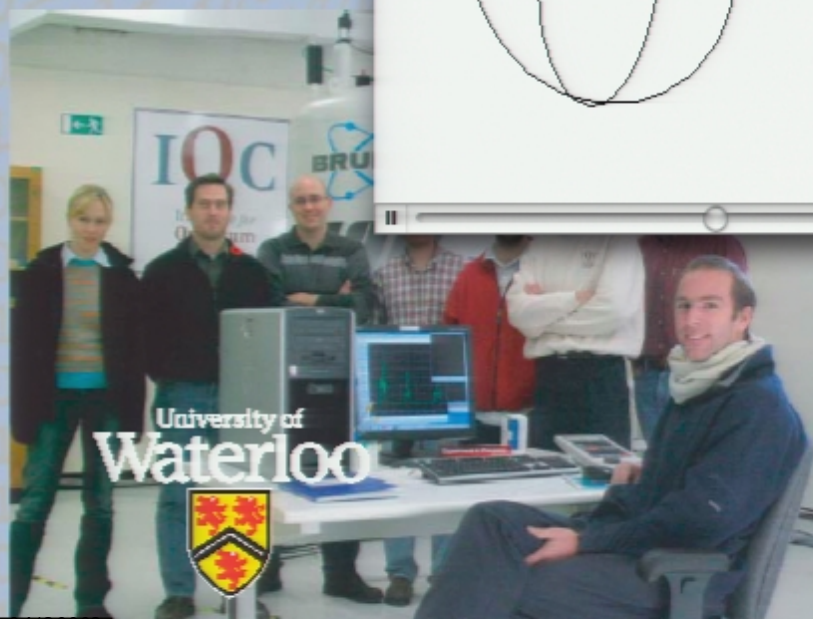
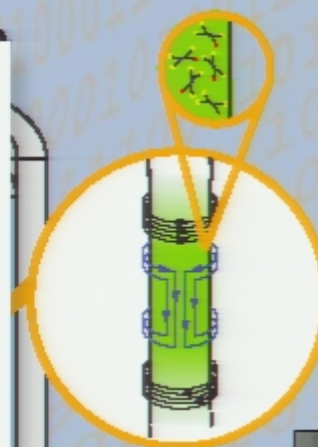
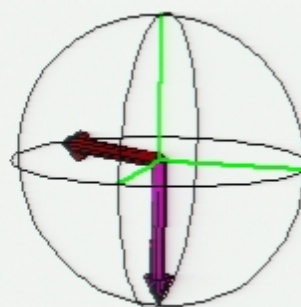
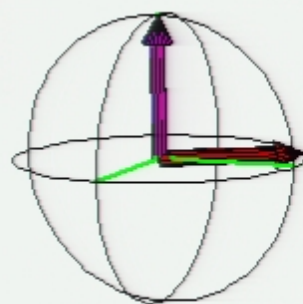
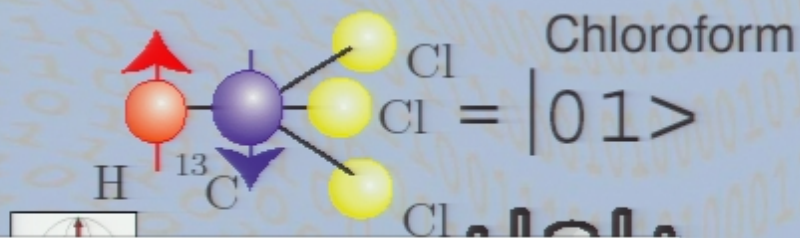
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Nuclear Magnetic Resonance



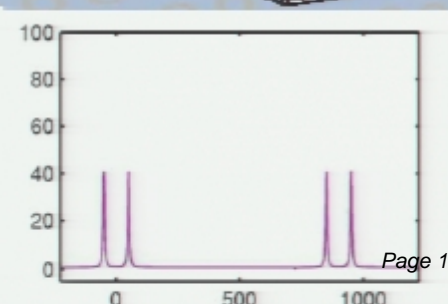
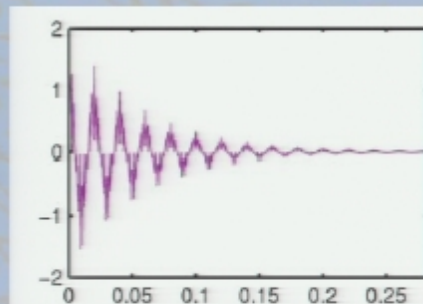
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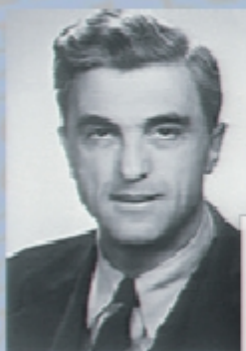
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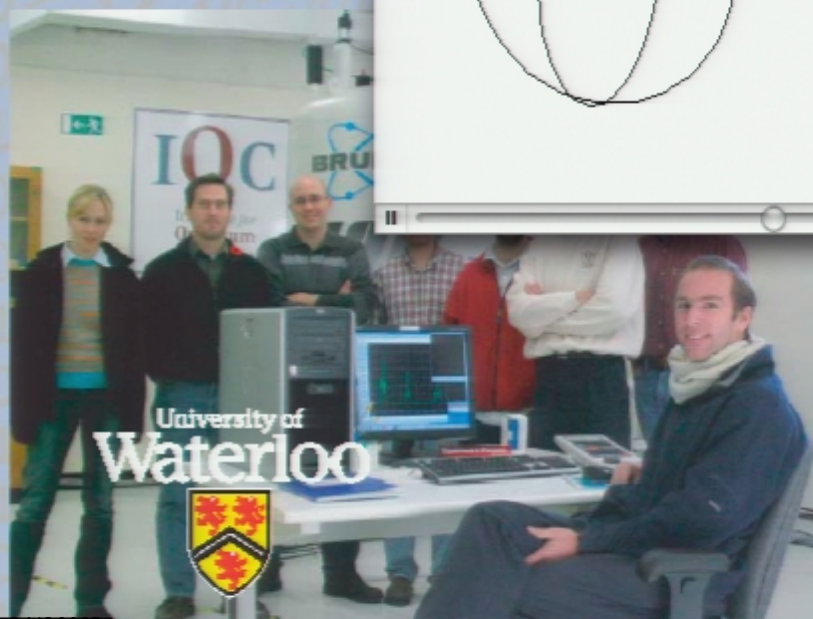
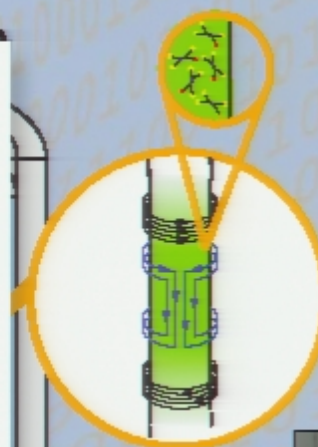
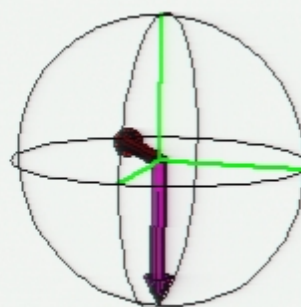
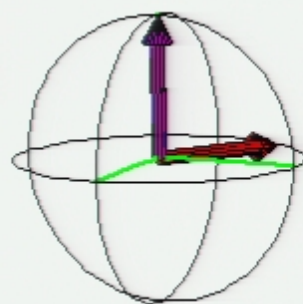
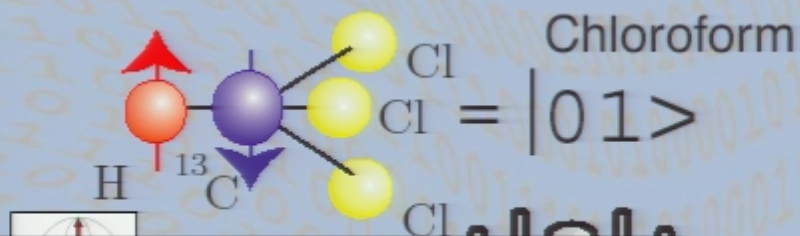
Bruker 700



Nuclear Magnetic Resonance



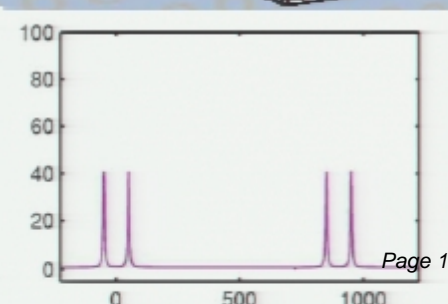
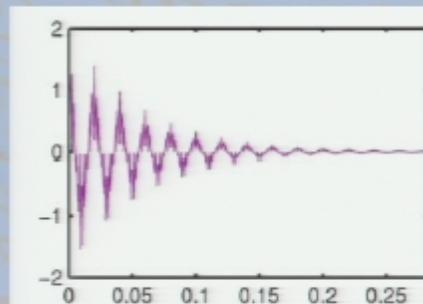
Bloch



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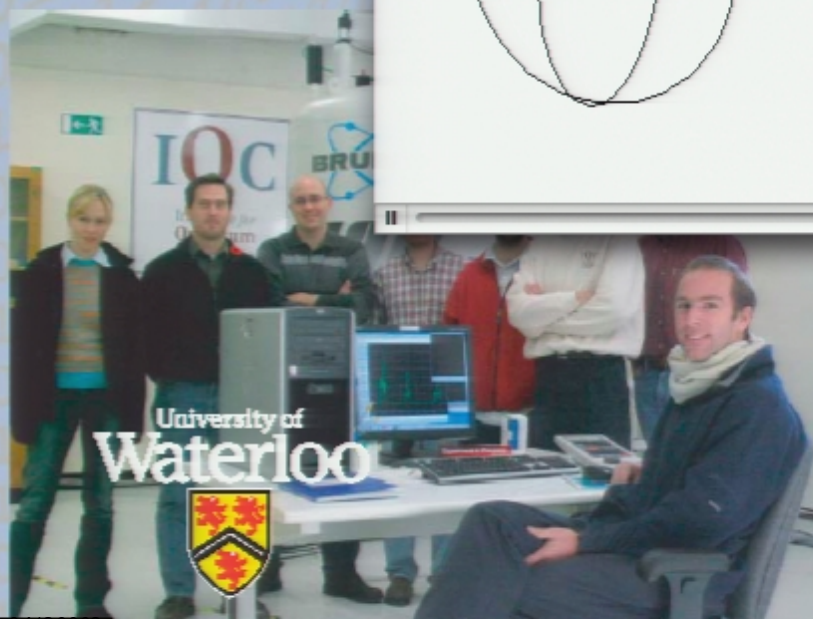
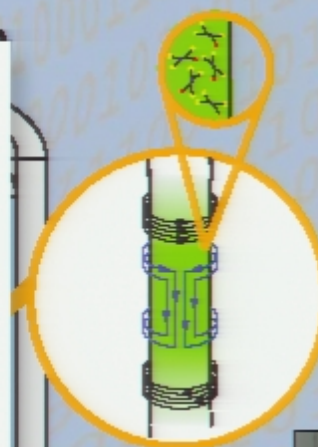
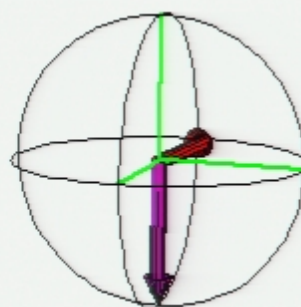
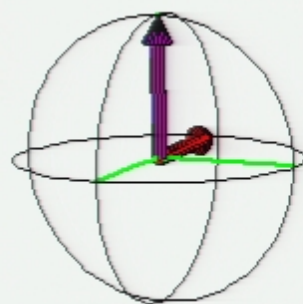
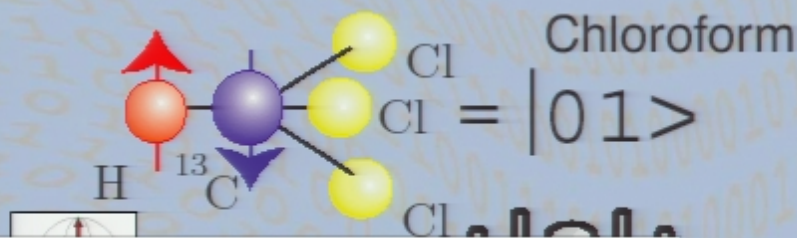
Bruker 700



Nuclear Magnetic Resonance



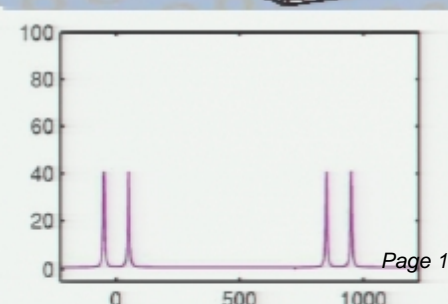
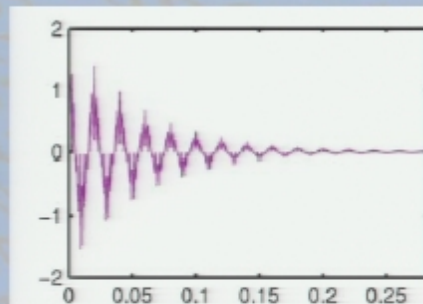
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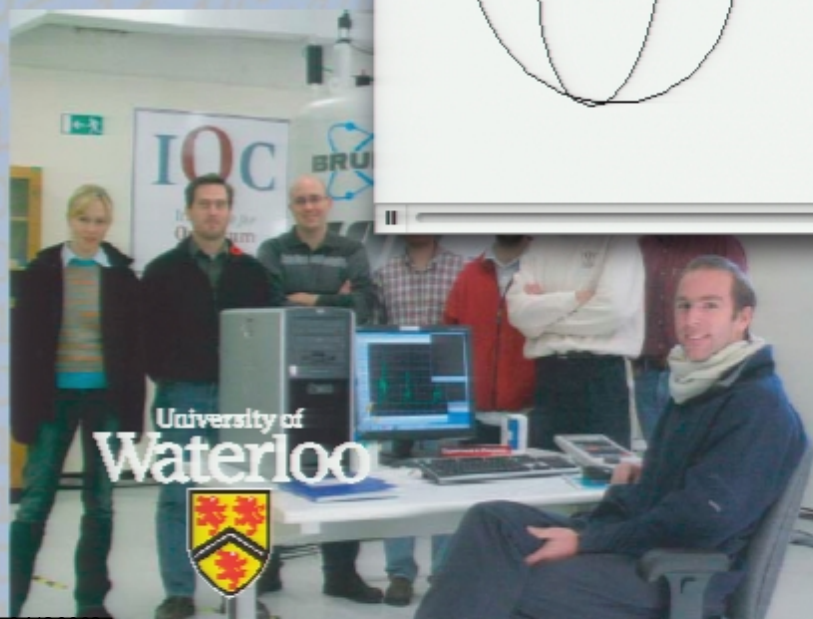
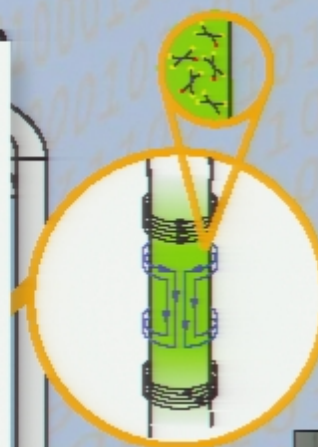
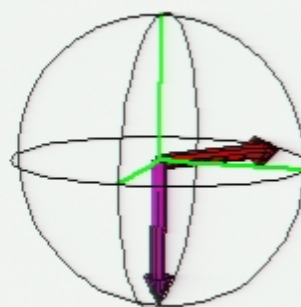
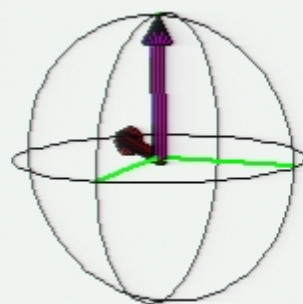
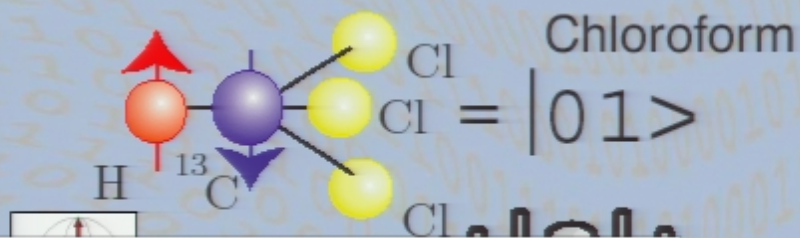
Bruker 700



Nuclear Magnetic Resonance



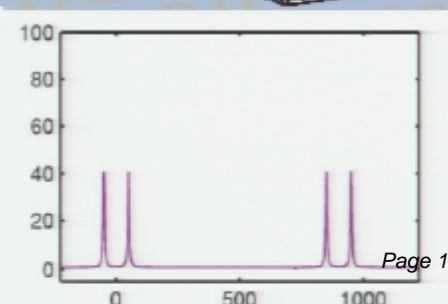
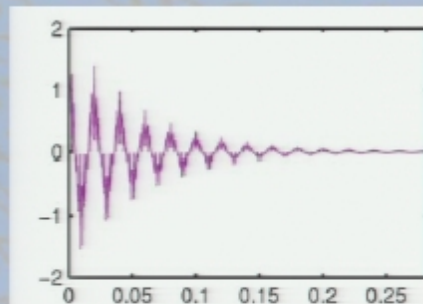
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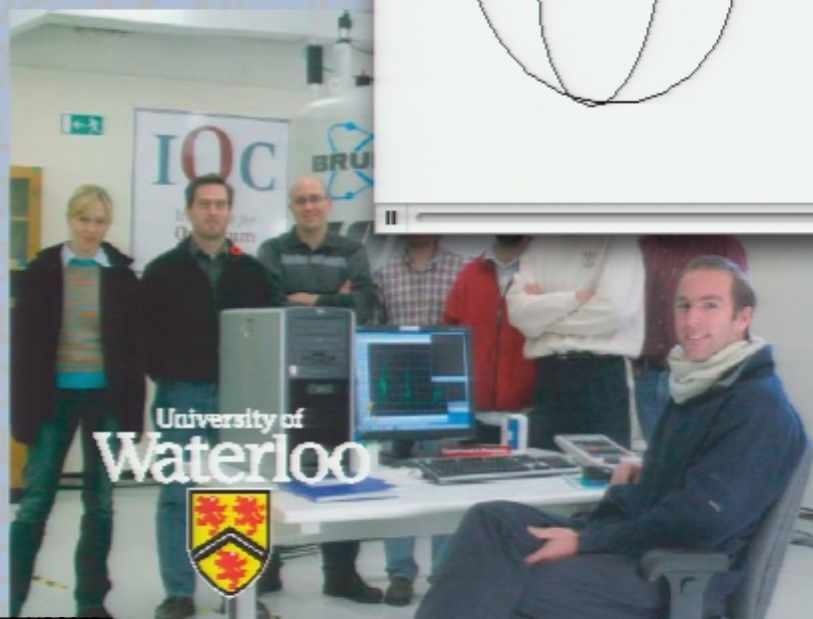
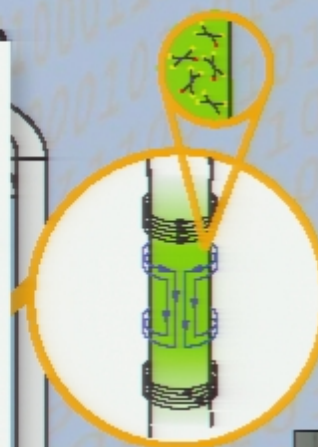
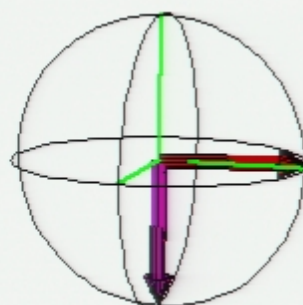
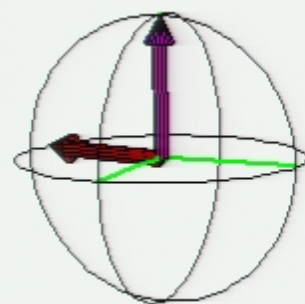
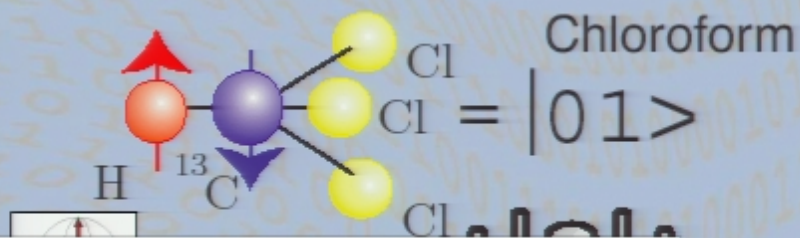
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Nuclear Magnetic Resonance



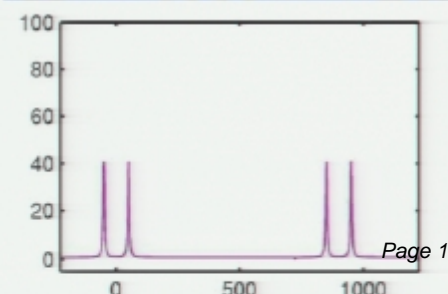
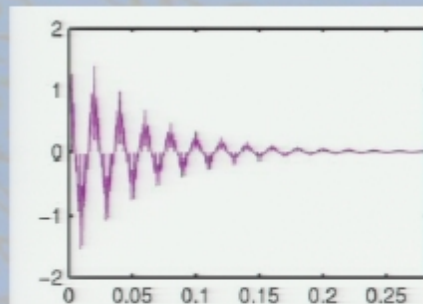
Bloch



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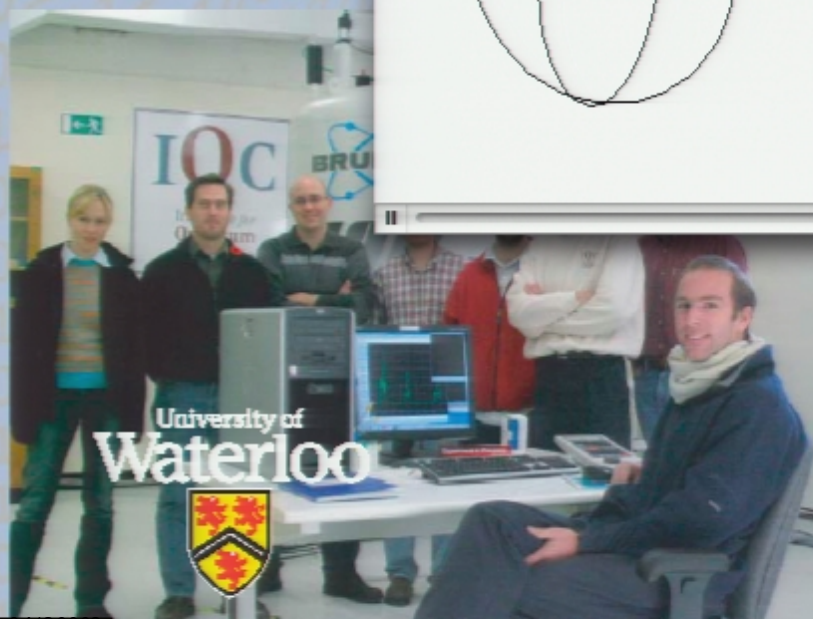
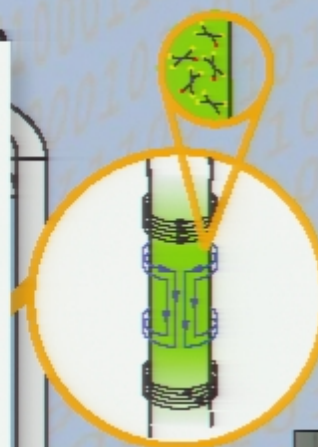
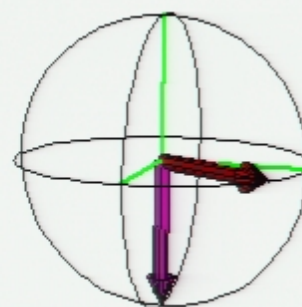
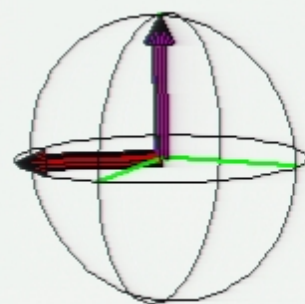
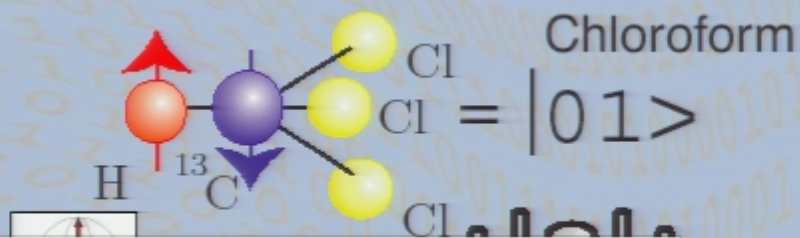
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Nuclear Magnetic Resonance



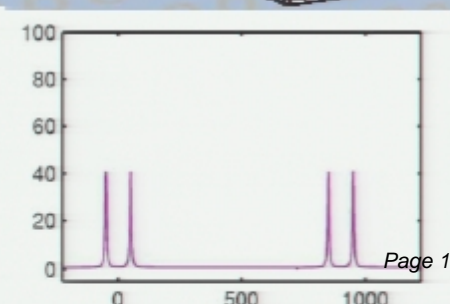
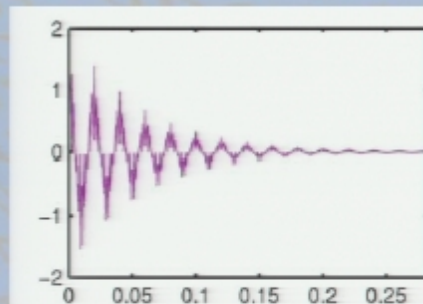
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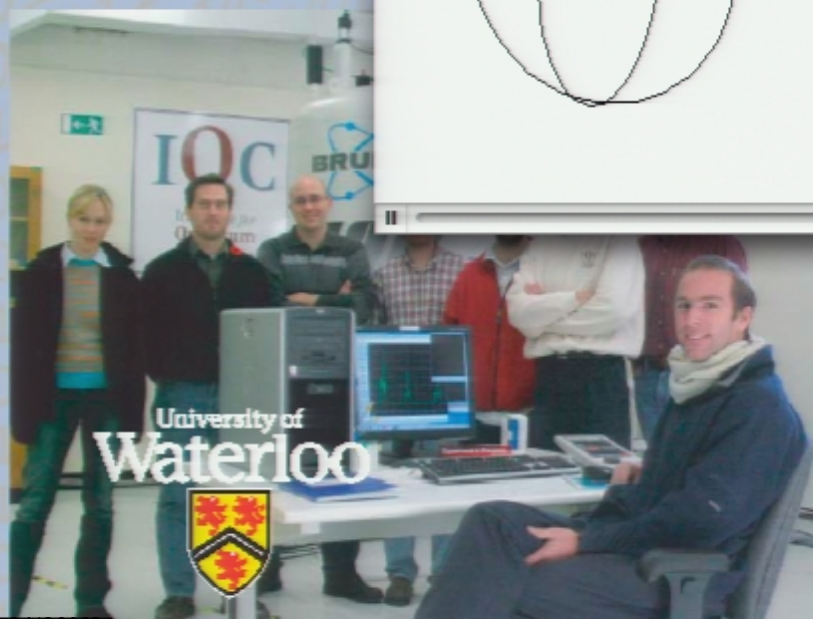
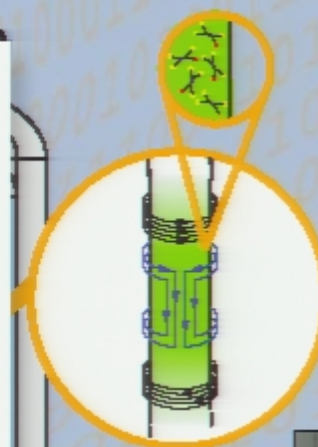
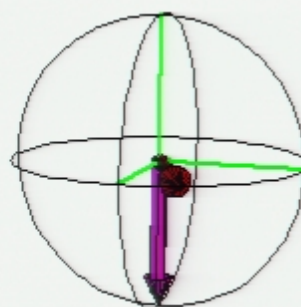
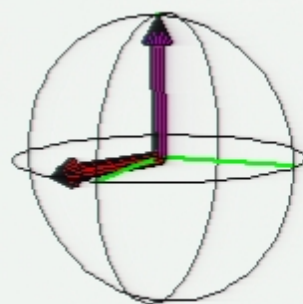
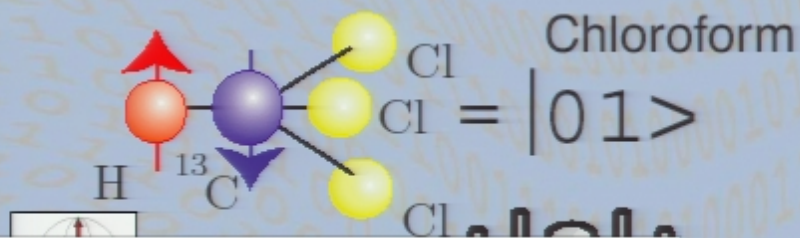
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Nuclear Magnetic Resonance



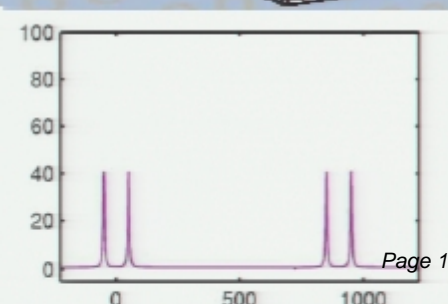
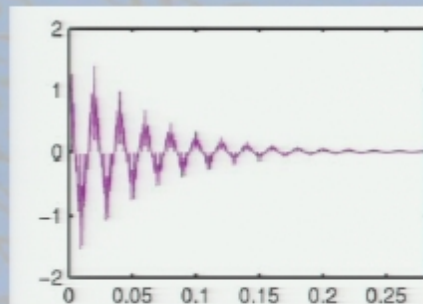
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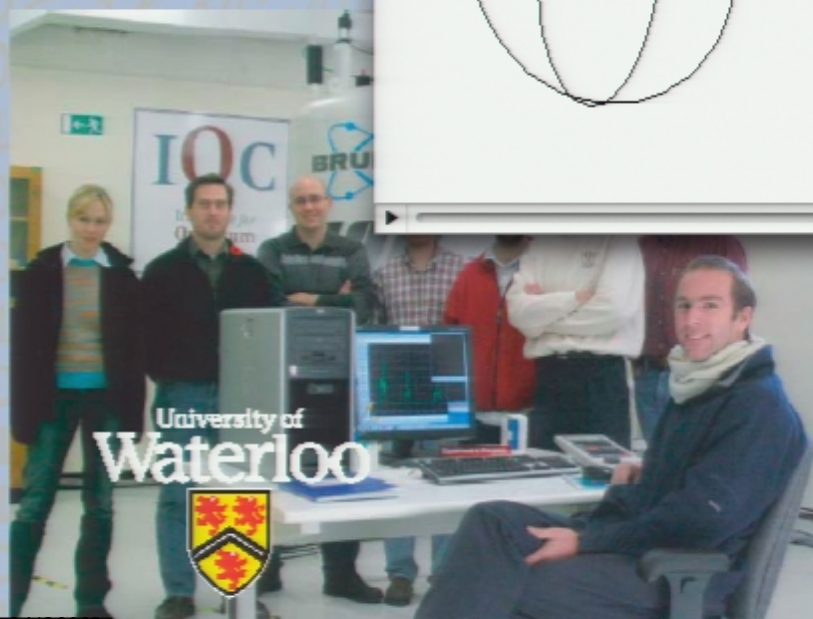
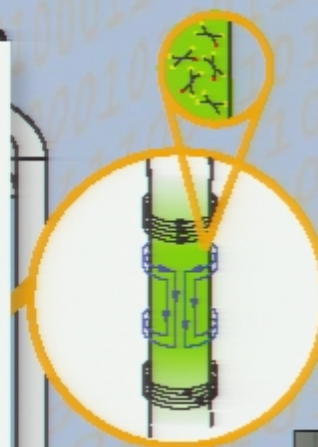
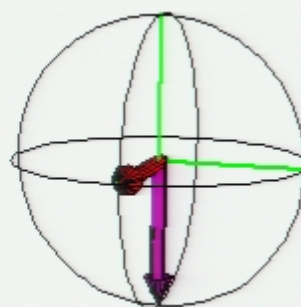
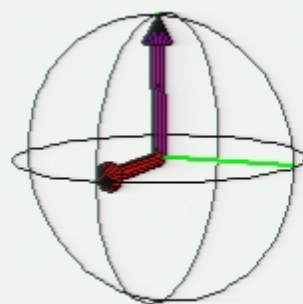
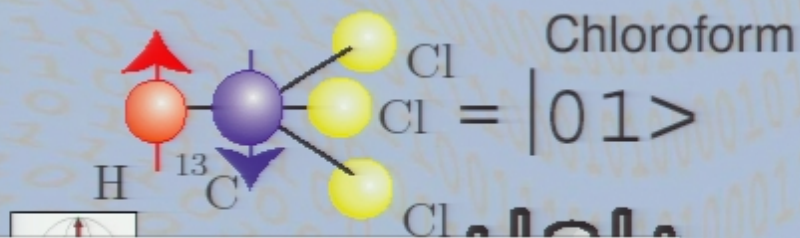
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Nuclear Magnetic Resonance



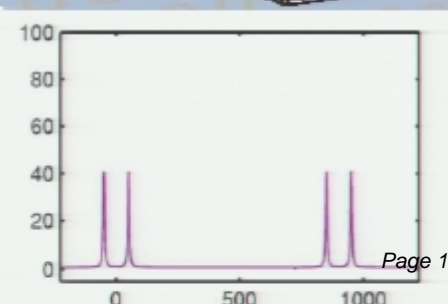
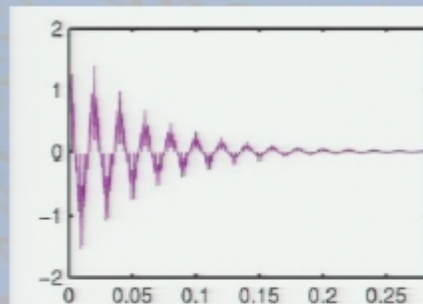
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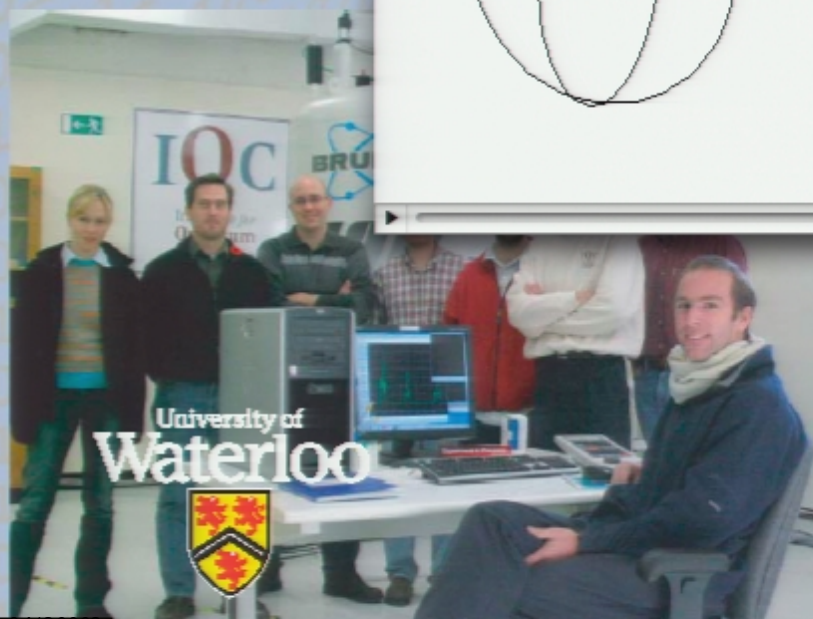
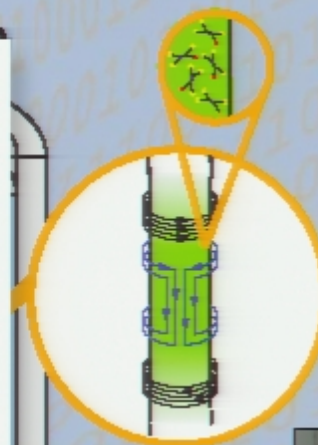
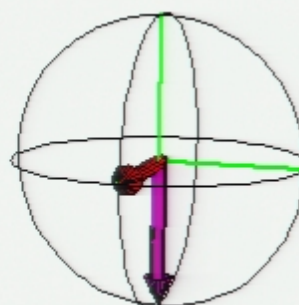
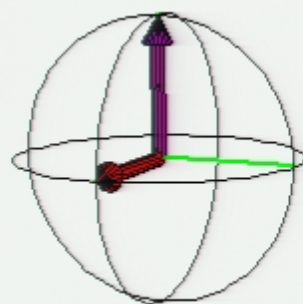
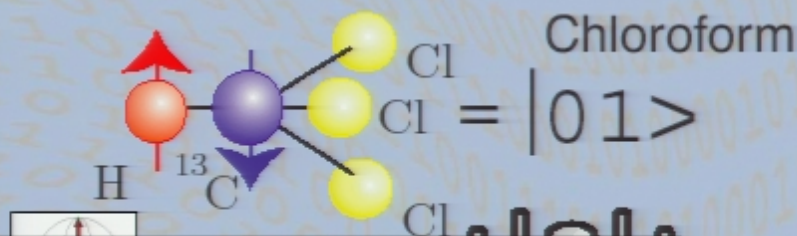
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Nuclear Magnetic Resonance



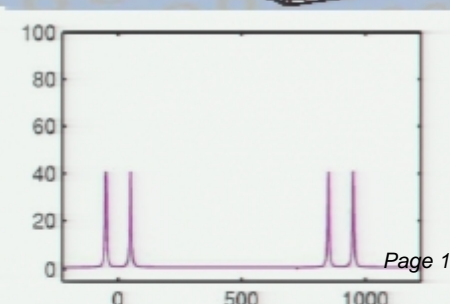
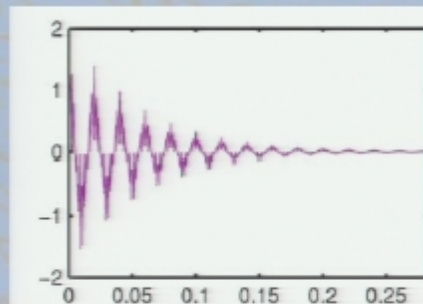
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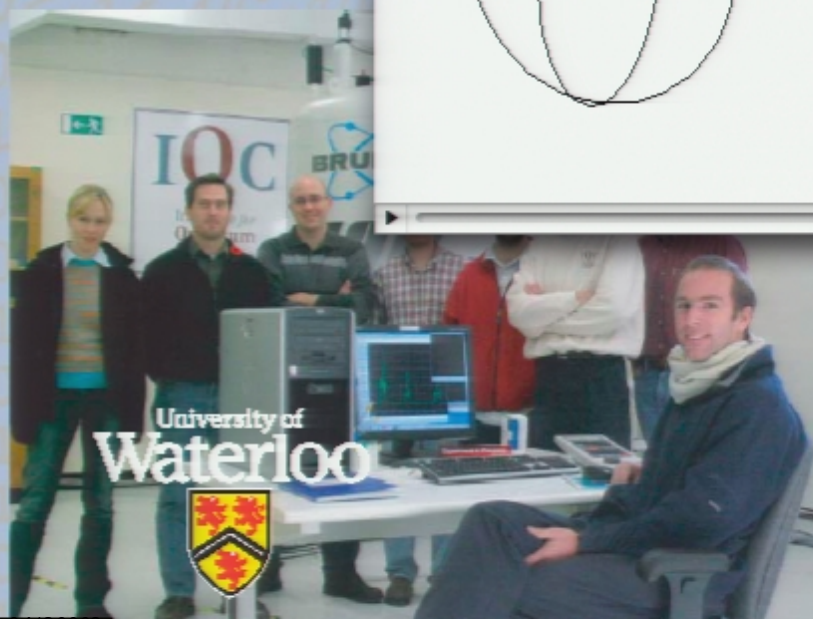
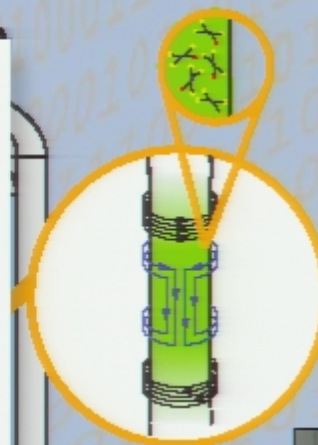
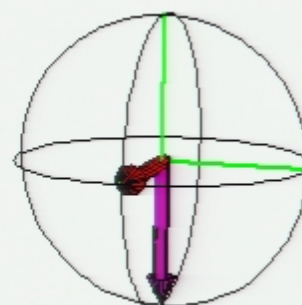
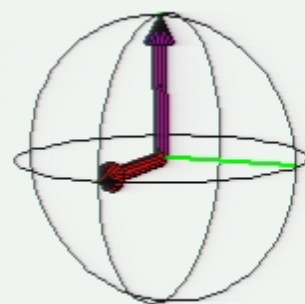
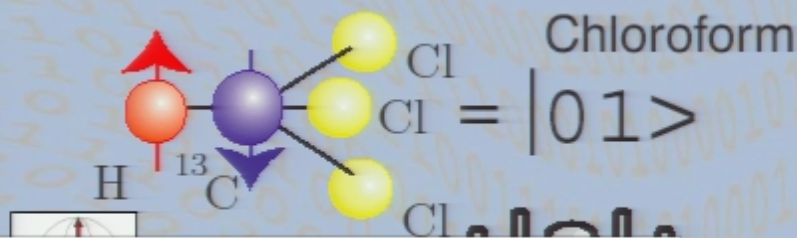
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Nuclear Magnetic Resonance



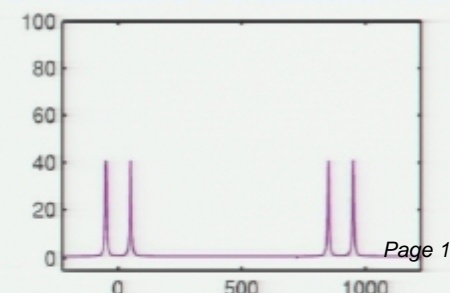
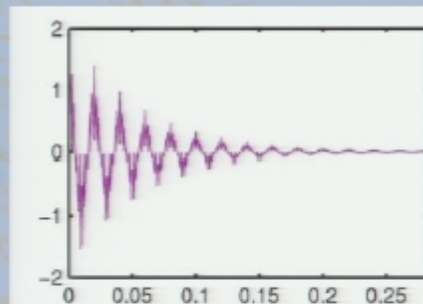
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Bruker 700



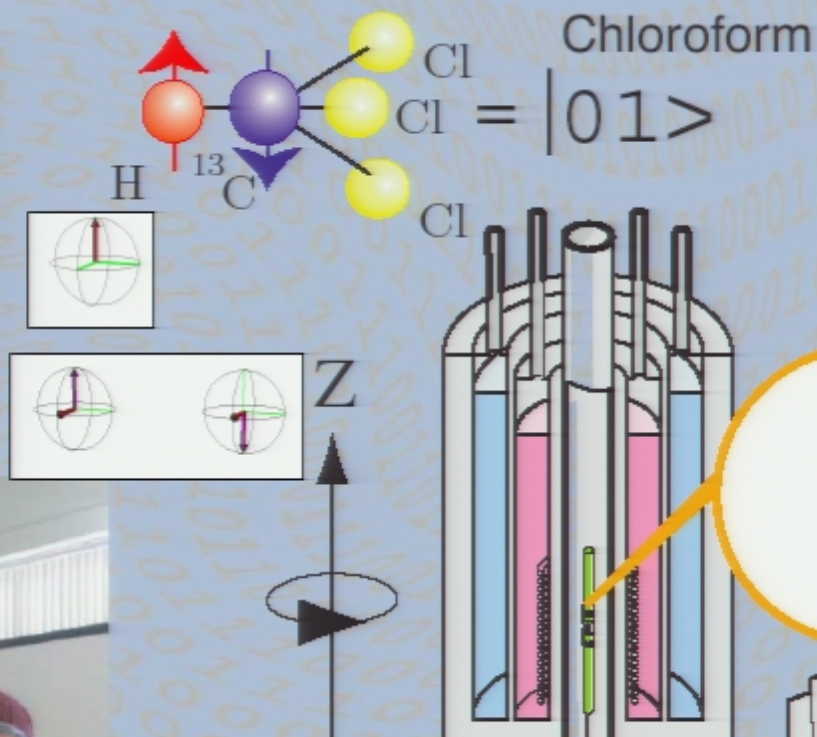
Nuclear Magnetic Resonance



Bloch



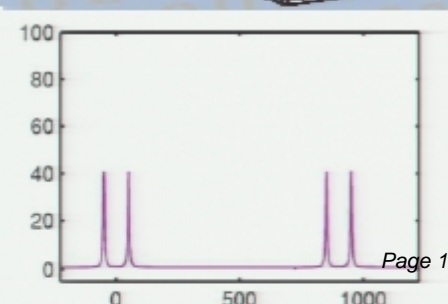
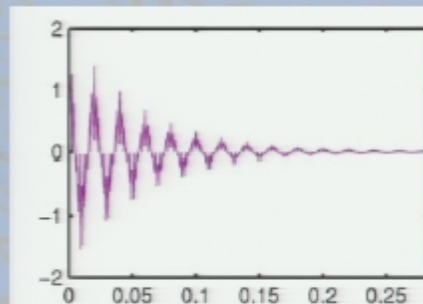
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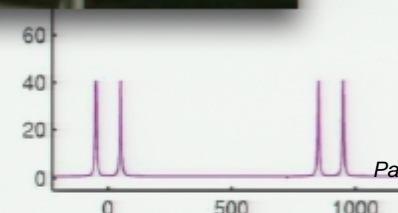
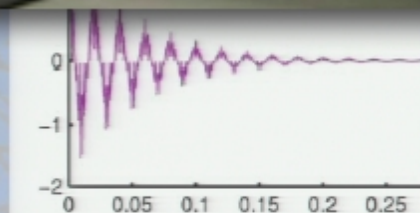
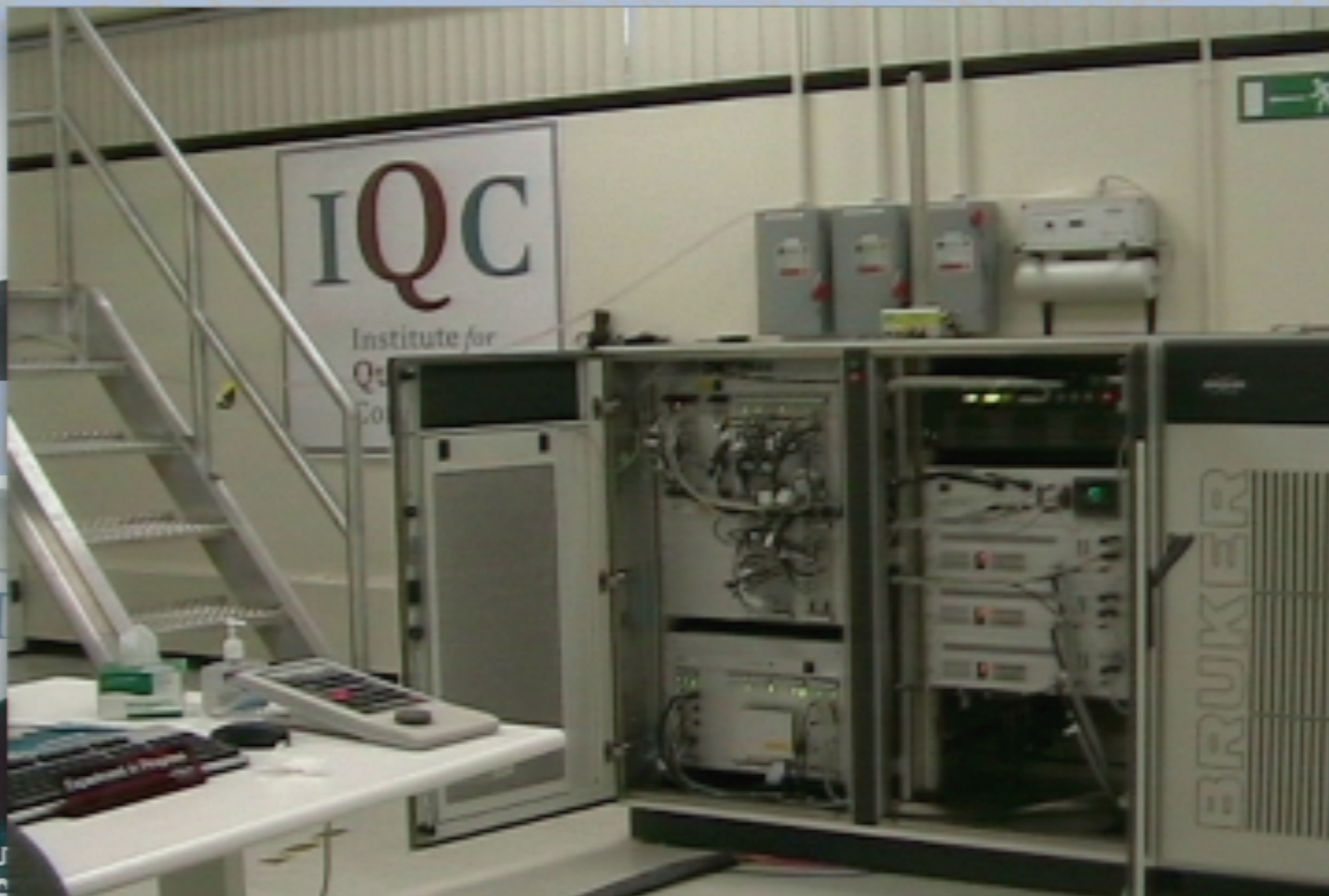
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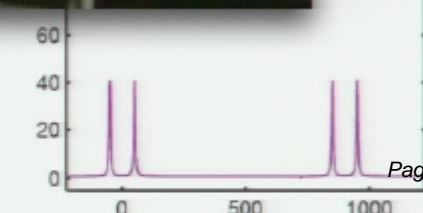
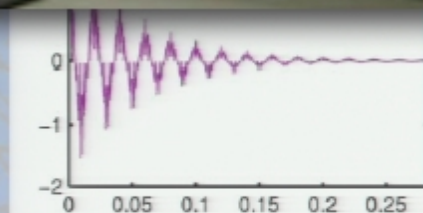
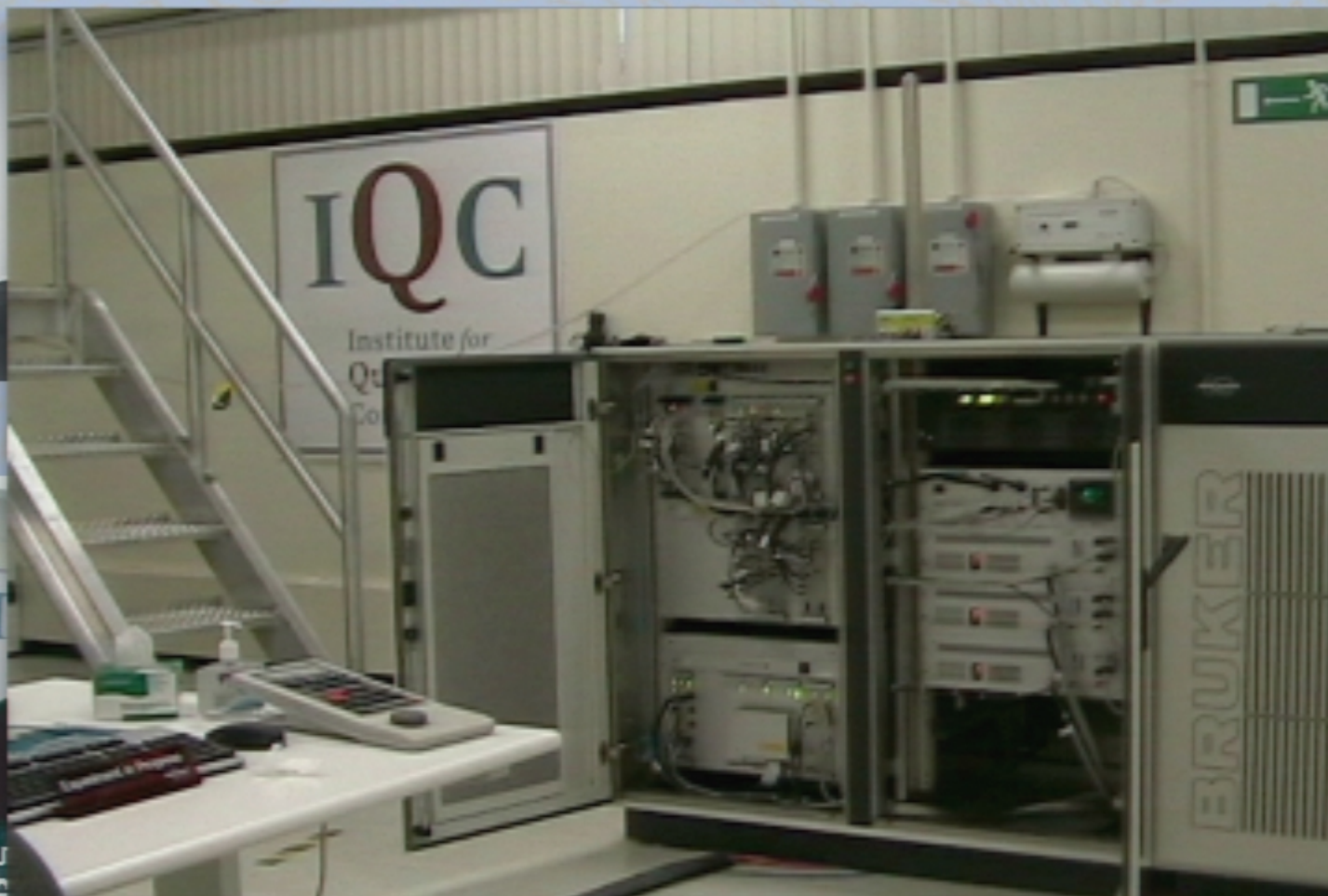
Bruker 700



Nuclear Magnetic Resonance



Nuclear Magnetic Resonance

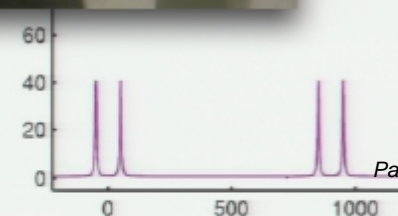
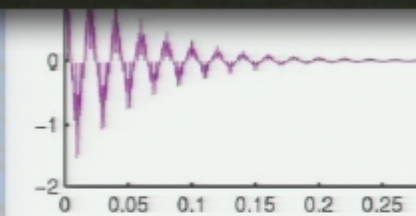


Nuclear Magnetic Resonance



Pirsa: 04120002

Bruker 700

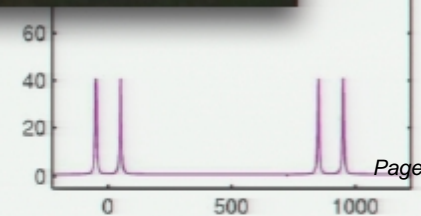
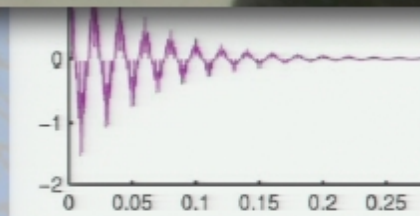


Nuclear Magnetic Resonance

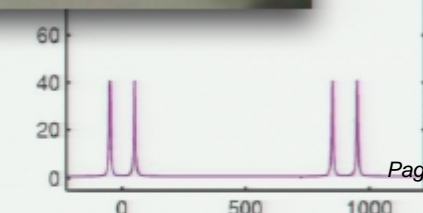
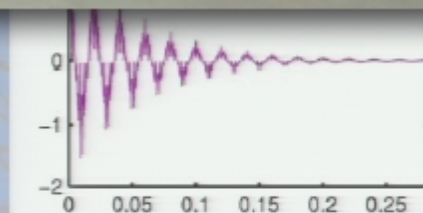


Pirsa: 04120002

Bruker 700



Nuclear Magnetic Resonance



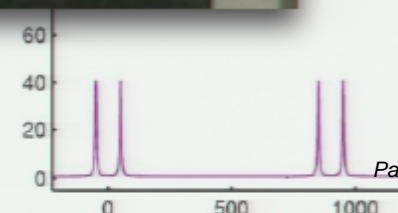
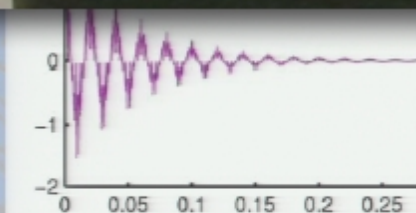
Bruker 700

Nuclear Magnetic Resonance

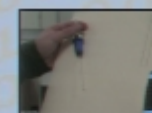


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Bruker 700

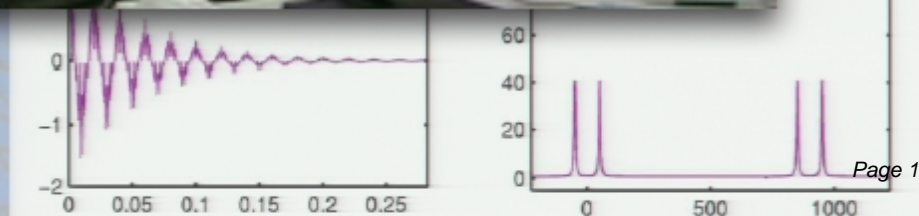


Nuclear Magnetic Resonance



Pirsa: 04120002

Bruker 700

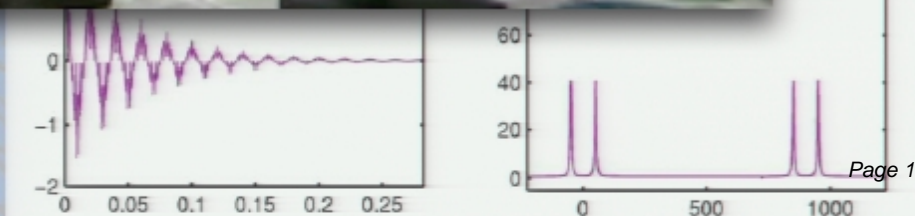


Nuclear Magnetic Resonance

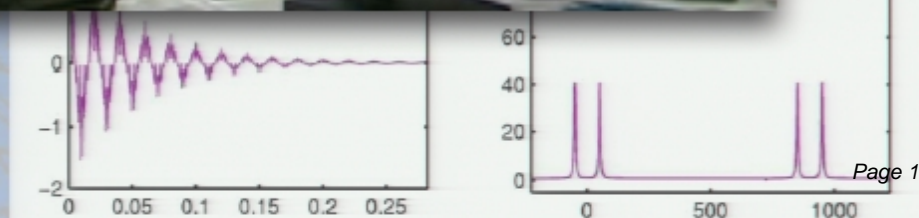


Pirsa: 04120002

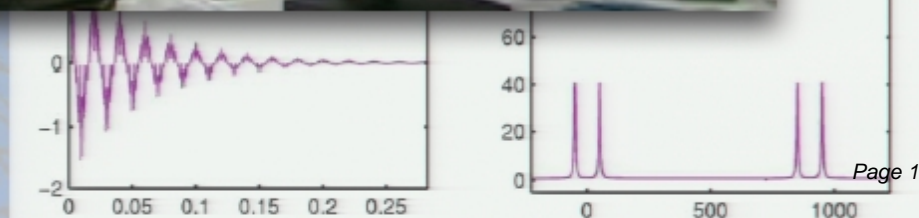
Bruker 700



Nuclear Magnetic Resonance



Nuclear Magnetic Resonance

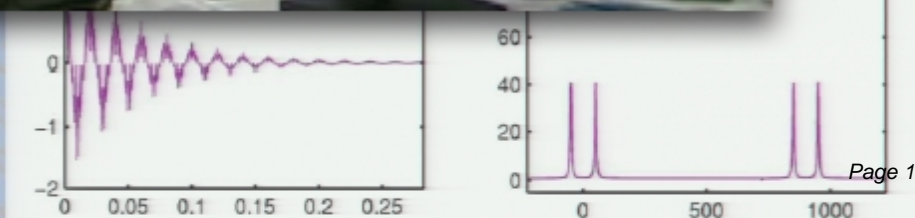


Nuclear Magnetic Resonance



Pirsa: 04120002

Bruker 700



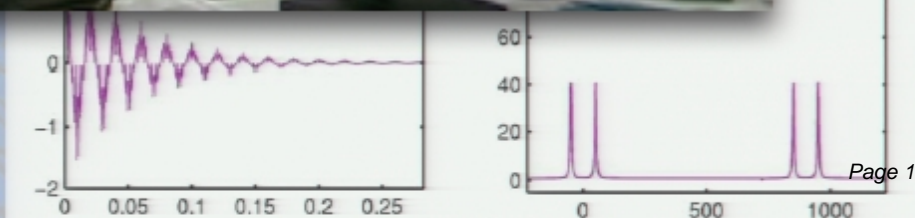
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Nuclear Magnetic Resonance



Pirsa: 04120002

Bruker 700

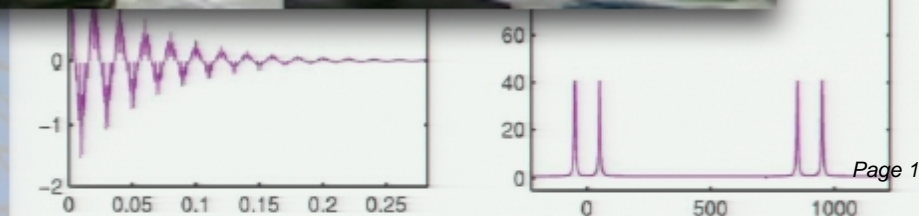


Nuclear Magnetic Resonance

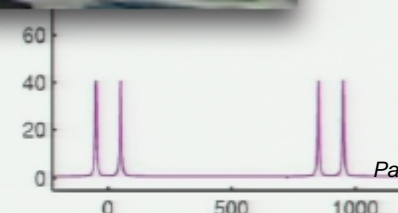
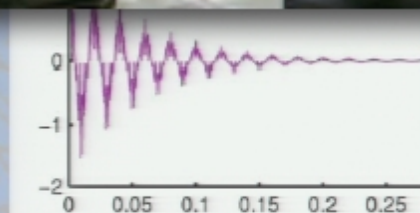


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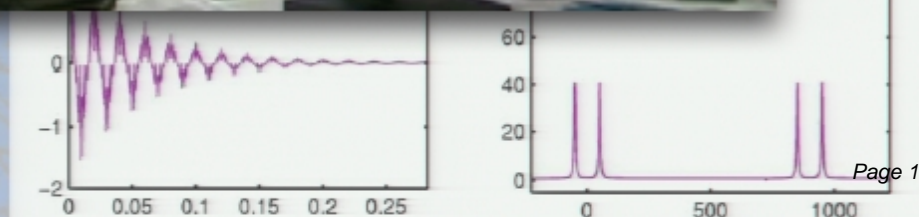
Bruker 700



Nuclear Magnetic Resonance



Nuclear Magnetic Resonance



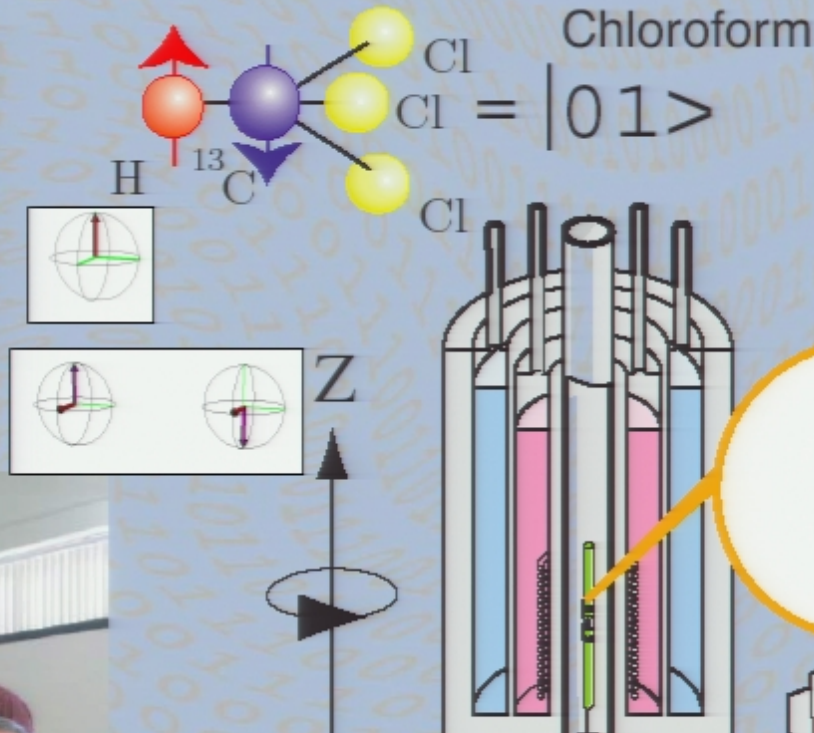
Nuclear Magnetic Resonance



Bloch



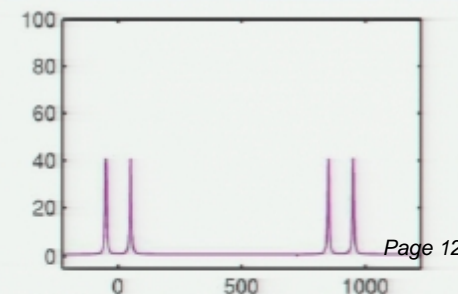
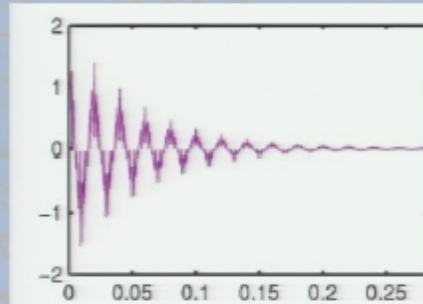
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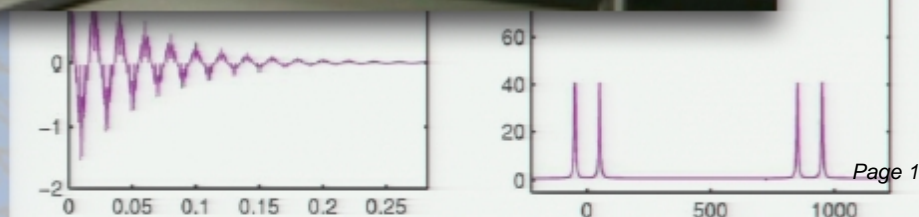
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Waterloo



Bruker 700



Nuclear Magnetic Resonance



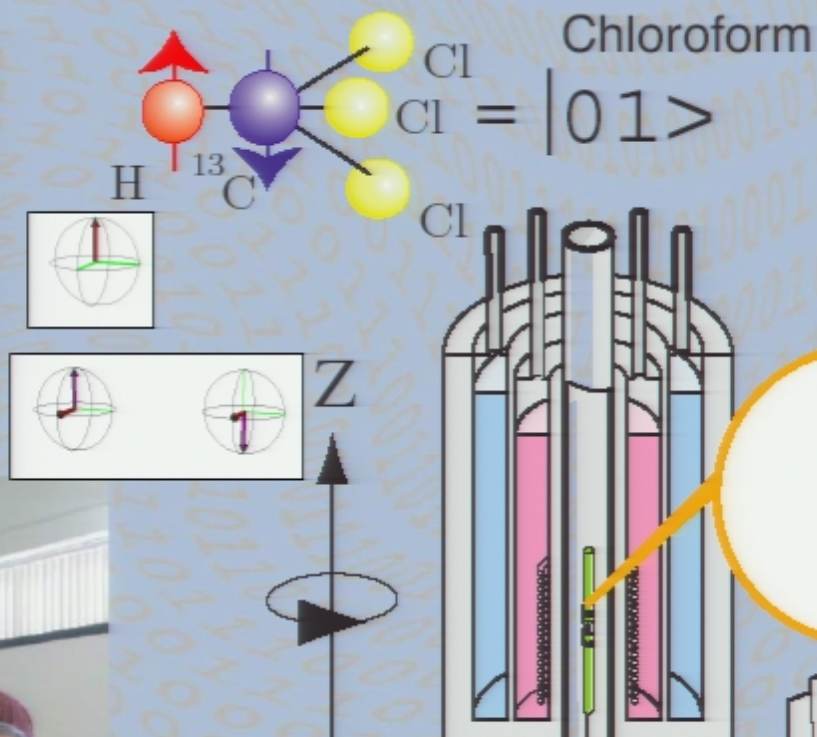
Nuclear Magnetic Resonance



Bloch



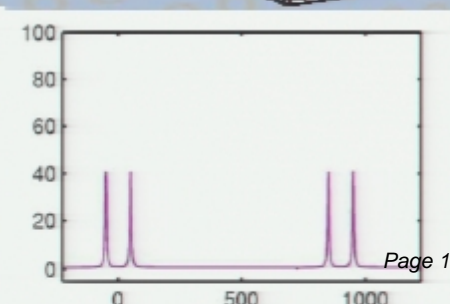
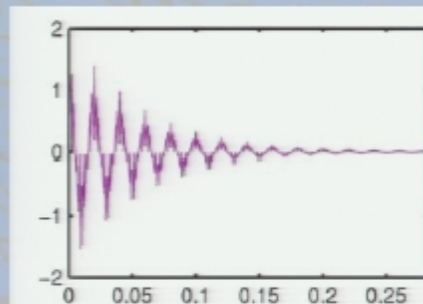
Purcell



University of
Waterloo

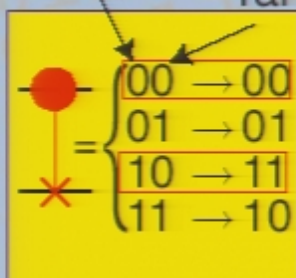


Bruker 700

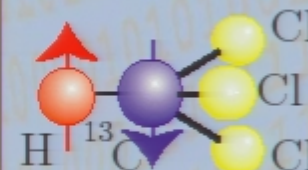
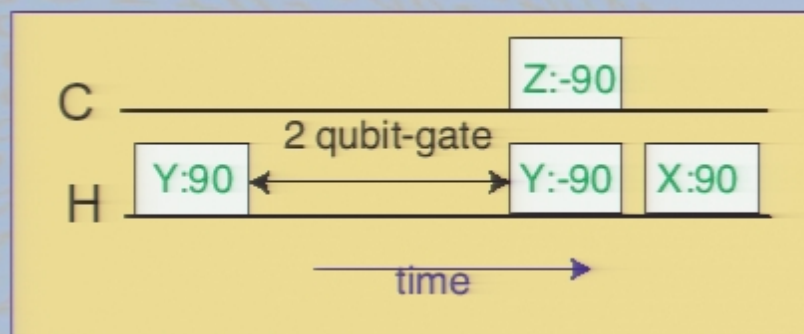


Quantum algorithms 101: the Control-NOT

Control-Not



Quantum circuit



Pre-compiler (Optimizer)

Bruker (machine) language

```

; Debug to track down error sources by doing partial error correction.
; Define C1C2
; Switch C1 = 1;
; Switch C2 = 1;
; Include "cipp.h"

; Global = 5; Global = 2; Global = 1;

; Create .1
; Global = 5; Global = 2; Global = 1;

; Pulse sequence
; Correction steps
; Create C1C2
; pulse C2_90 .25
; zz .25 C1 C2
; zpulse C1:.75;C2:
; pulse C2_90 .75
; pulse C2_90 .0
; refocus C1C2_180
; delay end .1
; Include "cipp.h"
    
```

```

; pulse C2_90 .25
; zz .25 C1 C2
; zpulse C1:.75;C2:
; pulse C2_90 .75
; pulse C2_90 .0
; refocus C1C2_180
    
```

```

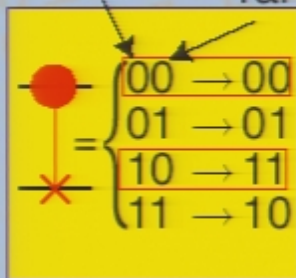
1 se
2 lhold LOCKM_OFF

; Initial virtual 180s
; Time: 0.000e+00 seconds

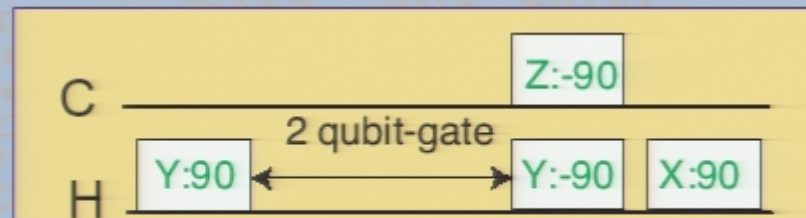
(C2_90:sp9 ph13 ):f1
3u
3u ipp13
0.71365m

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

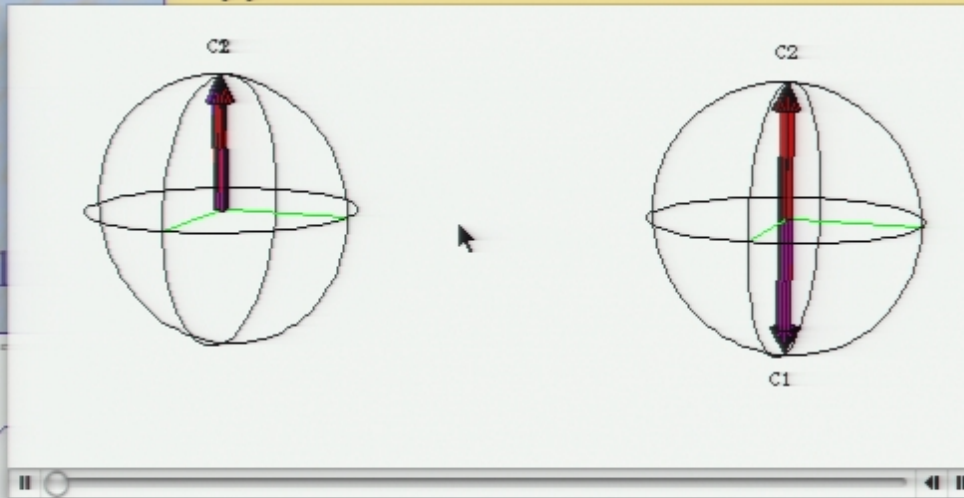
Control-Not Target



Quantum circuit



Pre-compile



uage

```
;; Debug to track down error source
```

```
#define CIObs
: ! $switch(HI) = 1;
: ! $switch(HI) = 1;
#include "ciop.h"
```

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```

; crate: .1

```

```
110: clocking = 5: clock
```

1. $\max_{1 \leq i \leq n} |x_i| \leq 1$

10

```
;; Correction steps
;;
```

• 7

1 22

11.15 C1 C2

```

: pulse M: 75;
: pulse C: 90 .

```

```

: pulse 0.10
: refocus 0.10

```

U ; 10

delay and .0

• 21

Atmel Corp., Norwell, Mass.

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01011

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0111011

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

```

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

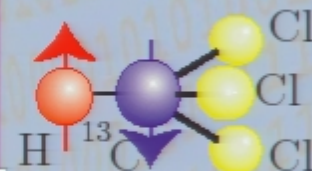
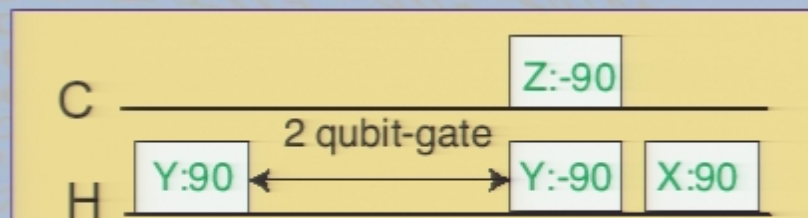
```


Quantum algorithms 101: the Control-NOT

Control-Not
Target

00	→	00
01	→	01
10	→	11
11	→	10

Quantum circuit



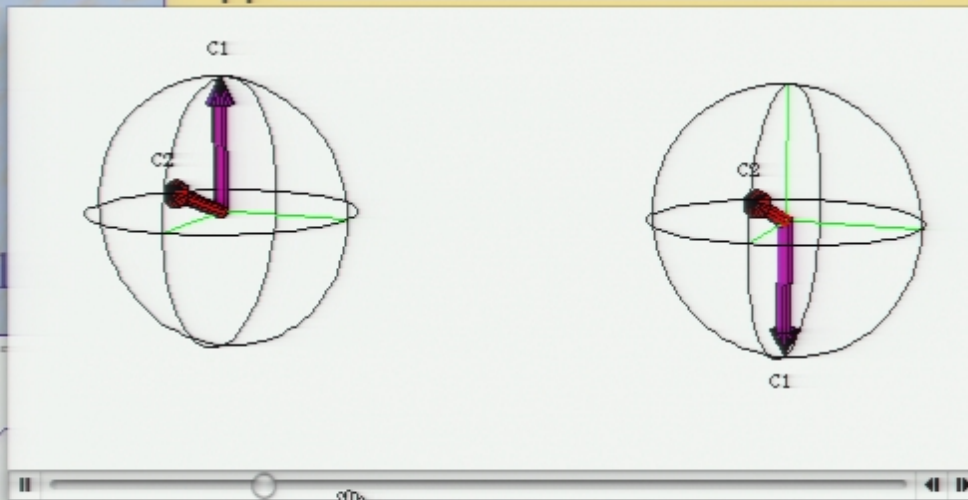
Pre-compile

```

// Debug to track down error source
#define C1C2
// Switch[0] = 1;
// Switch[0] = 1;
#include "cipp.h"

// Global = 5; Global = 2; Global

// Rate .1
// Global = 5; Global
// pulse coop 0.1
// Correction steps
//
// C1-C2
// pulse C2_90 .25
// zz .25 C1 C2
// zpulse C1:.75;C2:
// pulse C2_90 .75
// refocus C1C2_180
// delay end .1
//
#include "cipp.h"
    
```



uage

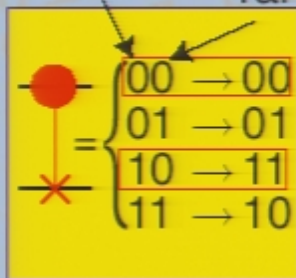
```

; pulse C2_90 .25
; zz .25 C1 C2
; zpulse C1:.75;C2:
; pulse C2_90 .75
; pulse C2_90 .0
; refocus C1C2_180
    
```

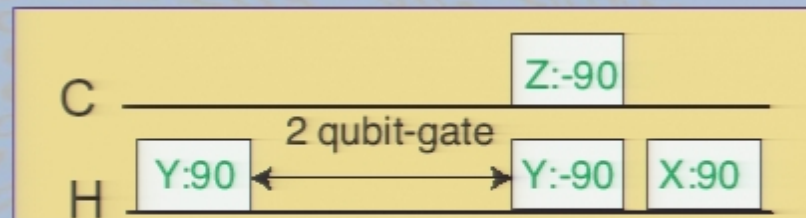
```

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

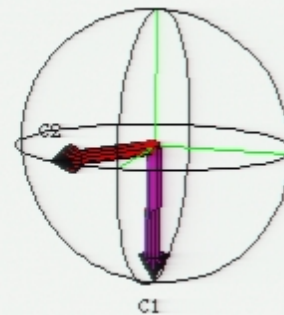
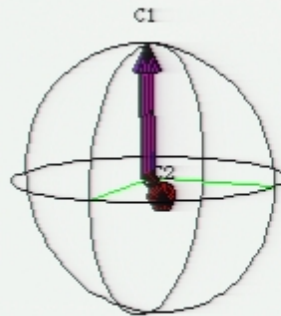
Control-Not Target



Quantum circuit



Pre-compile



uage

```
;; Debug to track down error source
```

```
#define CIObs
#ifdef HI
#ifdef HI2
#include "cio.h"
```

```
>> glcoeffs = 5; glcoeffs = 2; glcoeffs = 1;
```

```

; crate: 1

```

```

110 $locking = 5; $close;

```

```

: pulse nopp @W-2:0

```

```
;; Correction steps
```

...

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1. Pulse 120
2. 120/80

```

: spulse: M: 75;
: pulse: 75.00;

```

: pulse: C2_90 :
 : pulse: C2_90 :
 : pulse: C2_90 :

refocus client : pl

0. line ended .0

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Atacuda, Sept. 201

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011100

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

```

3u
  CI_90:ap9 ph2
3u
3u app11
0.711659
3u
3u
  CI_90:ap9 ph2
  Cu_app15 app
3u
  CI_90:ap9 ph2
  Cu_app15 app
3u Eq1:F2
3u Eq2:F1
50ms ph0.2
100ms
1bold 12CTM ON

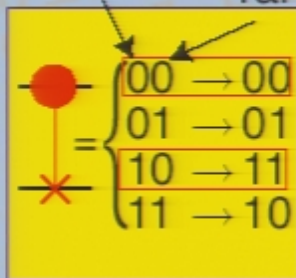
```

```

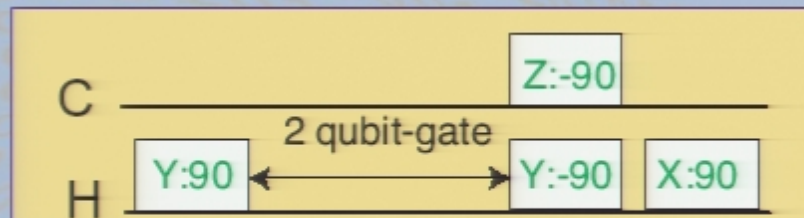
3u_
3u_ipp13
0.71365m
8u
8u
(C2_90:sp9_ph19):f1
6u_ipp15_ipp19
8u
(C2_90:sp9_ph20):f1
6u_ipp15_ipp20

```

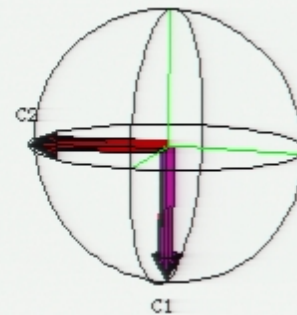
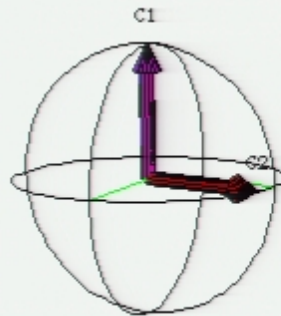

Control-Not Target



Quantum circuit



Pre-compile



uage

```
;; Debug to track down error source
```

```
#define CLOBE
#ifdef __GLIBC__
#define __GLIBC__ 2
#endif
#include "cipp.h"
```

```
1> $lockArg = 5; $lockStep = 2; $lockArg
```

100

110

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11/11/2011 11:11:11 AM

1. pulsw C2 90 .
2. 22 15 C1 C2

```

: xpulse W: 75:
: pulse CI 90:

```

```

: pulse C1 30
: refocus C1C2

```

delay end 0

A graph of a function on a coordinate plane. The x-axis ranges from 0 to 4, and the y-axis ranges from 0 to 4. The function is a curve that starts at (0, 3), decreases to a minimum at (1, 1), increases to a maximum at (3, 3), and then decreases to (4, 1). The curve is concave up in the interval (0, 1) and concave down in the interval (1, 3).

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

```

3u
| C2_90:sp9 ph19
3u
3u ipp13
0.71365m
8u
8u
0.71365m
6u ipp15 ipp19
8u
|C2_90:sp9 ph1
6u ipp15 ipp19
3u fq1:f1
3u fq2:f1
99% above
100%
lhold 120000_ort
8u
(C2_90:sp9 ph19):f1
6u_ipp15 ipp19
8u
(C2_90:sp9 ph20):f1
6u_ipp15 ipp20

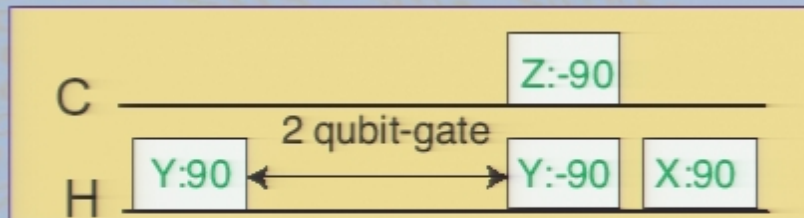
```

Control-Not Target

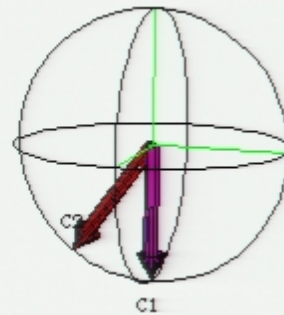
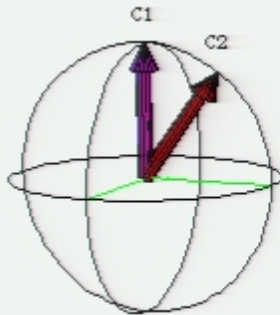
Diagram illustrating the mapping of the 4-bit input to the 4-bit output for the 4-bit multiplexer:

00	→	00
01	→	01
10	→	11
11	→	10

Quantum circuit



Pre-compil



uage

```
;; Debug to track down error source
```

```
#define CLOCKS
: !switch[01] = 1;
: !switch[02] = 1;
#include "cipp.h"
```

```
>> $locHng = 5; $locStp = 2; $l
```

```

; state: .1

```

```

110  $locking = 5; $least

```

```

; pulse noop @W2-;0

```

```
;; Correction steps
```

11-12-13

Pulse 72-90
Temp 36.8-37.2

```

: spulaw Mt. 75;
: spulaw Mt. 80;

```

```

: pulse CI 90 .
: pulse CI 90 .
: pulse CI 90 .

```

: pu

10. delay end .0

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```
#include "text.h"
```

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011100

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

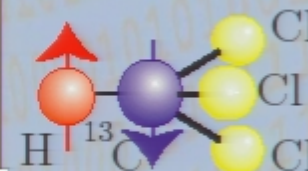
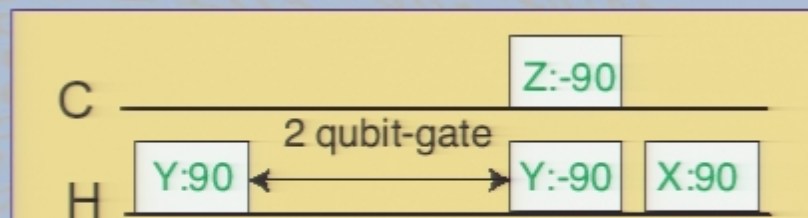
[illegible]

Quantum algorithms 101: the Control-NOT

Control-Not
Target

00	→	00
01	→	01
10	→	11
11	→	10

Quantum circuit



Pre-compil

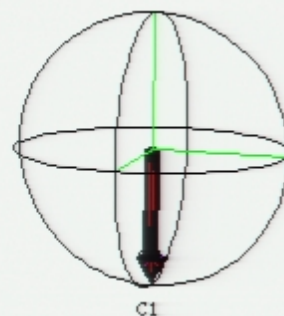
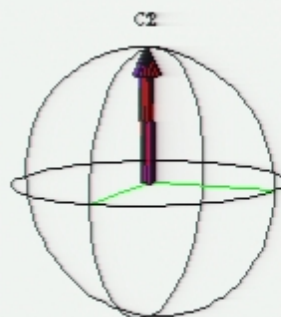
```

; Debug to track down error source
; Define C1C2
; Switch C1 = 1;
; Switch C2 = 1;
; Include "cipp.h"

; Clocking = 5; ClockStep = 2; ClockStep = 1;

; Create .1
; Clocking = 5; ClockStep = 1;

; Pulse loop
; Correction steps
; Create C1-C2
; pulse C2_90 .25
; zz .25 C1 C2
; zpulse C1:.75;C2:
; pulse C2_90 .75
; pulse C2_90 .0
; refocus C1C2_180
; delay end .1
; C
; Include "cipp.h"
    
```



uage

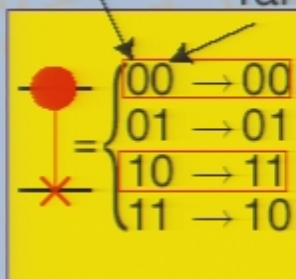
```

; pulse C2_90 .25
; zz .25 C1 C2
; zpulse C1:.75;C2:
; pulse C2_90 .75
; pulse C2_90 .0
; refocus C1C2_180
    
```

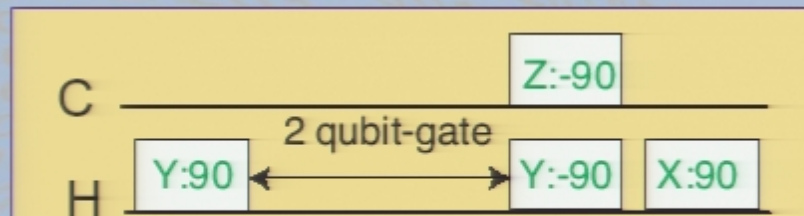
```

3u
3u app13
0.71365m
8u
8u
(C2_90:sp9 ph19):f1
6u_ipp15 ipp19
8u
(C2_90:sp9 ph20):f1
6u_ipp15 ipp20
    
```

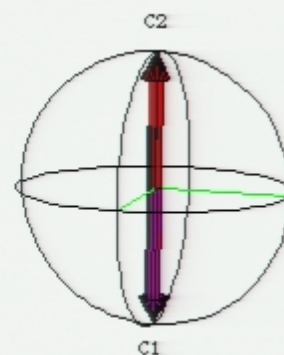
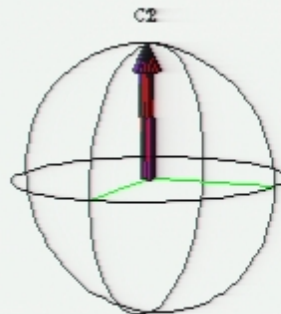
Control-Not
Target



Quantum circuit



Pre-compile



uage

```

:: Debug to track down error source

```

```
#define CIObs
: $switch[0] = 1;
: $switch[0] = 1;
#include "cio.h"
```

```
1> $locStart = 5; $locStep = 2; $l
```

10

```

; crate .1
;;c

```

```
11> $locking = 5; $lockst
```

```

; pulse loop @W 2-10
;;

```

```
;; Correction steps
...
```

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Volume 17, 1990

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: pulsa C2_30
 : pulsa C2_30

refocus CIC • n1

delay end .0

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

```

3u
(C2_90:sp9 ph19) :f1
3u_ipp13
0.71365m
8u
8u
(C2_90:sp9 ph19) :f1
3u_ipp15_ipp19
8u
(C2_90:sp9 ph20) :f1
3u_ipp15_ipp20
500000000
10000
lhold 100000000

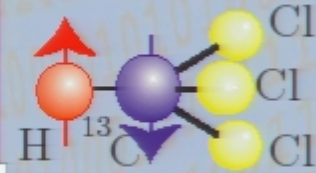
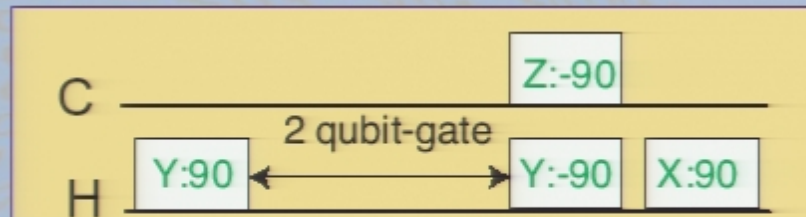
```


Control-Not Target

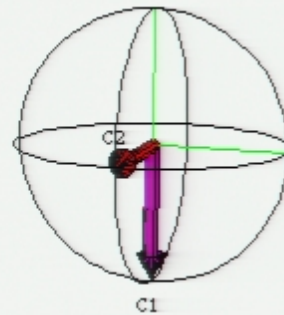
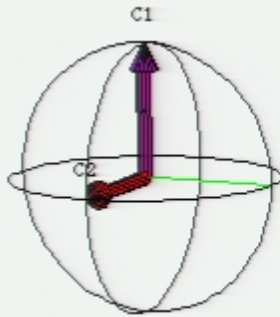


00	→	00
01	→	01
10	→	11
11	→	10

Quantum circuit



Pre-compil



uage

```
% Debug to track down error source
define Clob
%switch W1 = 1;
%switch W2 = 1;
#include "cloop.h"

% glong = 5; glongStep = 2; S1

% rate .1
%% glong = 5; glongStep = 2; S1

% pulse loop W1=1;
%%
%% Correction steps
%%
%comp C1 -> C2
% pulse C2 90
% zz .25 C1 C2
% pulse Mz .75;
% pulse C1 90
% refocus C1C2
% delay end .5

%
#include "exit_dad"
```

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

```

| CI_90:sp9 ph
Ju
Ju app13
0.71325
Su
| CI_90:sp9 ph
Su
6u app15 app
| CI_90:sp9 ph
6u app15 app
Ju eq1:F2
Ju eq2:F1
gms ph-e
100s
lhold INCH ON

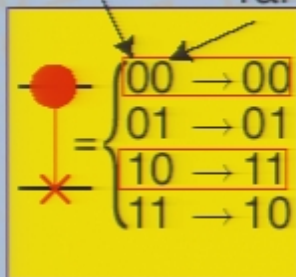
```

```

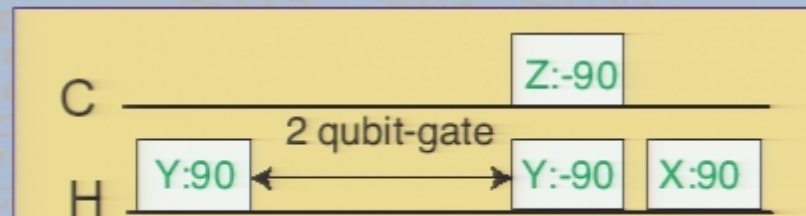
3u_
3u_ipp13
0.71365m
8u
8u
(C2_90:sp9_ph19):f1
6u_ipp15_ipp19
8u
(C2_90:sp9_ph20):f1
6u_ipp15_ipp20

```

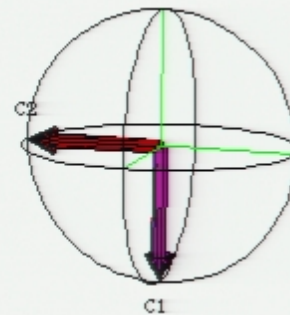
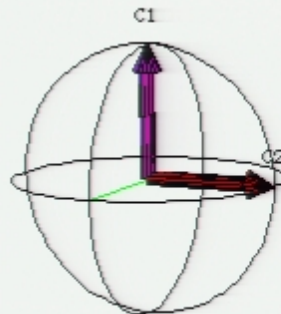
Control-Not Target



Quantum circuit



Pre-compile



uage

```
;; Debug to track down error source
```

```
#define CIObs
#ifdef CIObs
#include "cio.h"
#endif
```

```
1> $lockIng = 5; $lockStep = 2; $l
```

100

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101

555

27

1. Pulse CI 90.3
2. 15 CI CI

```

: pulse W: 75:
: pulse C: 90:

```

```

: pulse C1 10
: refocus C1C2

```

delay end .0 / 100

100

24

10

01010

100

011101

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

```

3u
| C2 90:wp9 phd1
3u
3u app13
0.711625
3u
3u
| C2 90:wp9 phd1
6u app15 phd1
| C2 90:wp9 phd1
6u app15 app1
3u eq1:f1
3u eq2:f1
9000 phd1
1000
lhold INCH OFF

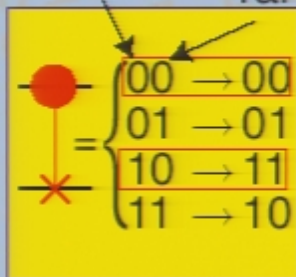
```

```

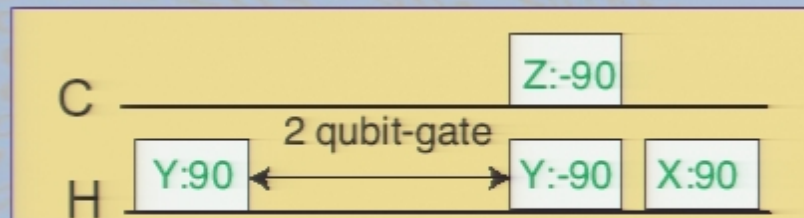
3u_
3u ipp13
0.71365m
8u
8u
(C2_90:sp9 ph19):f1
6u_ipp15 ipp19
8u
(C2_90:sp9 ph20):f1
6u_ipp15 ipp20

```

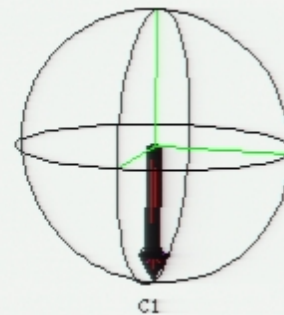
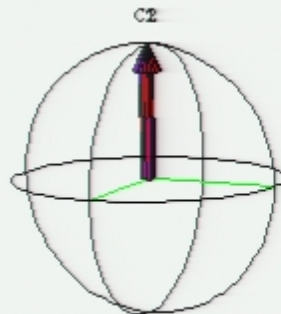

Control-Not Target



Quantum circuit



Pre-compile



uage

```
;; Debug to track down error source
```

```
#define CIObs
#ifdef HI
#ifdef HI2
#include "cio.h"
```

```
>> glcoeffs = 5; glcoeffs = 2; glcoeffs = 1;
```

```

; write: .l

```

```

110  $locking = 5; $close;

```

```

: pulse nopp @W-2:0

```

```
;; Correction steps
```

...

11/11/2011 11:11 AM

Pulse 120

: spulaw M: 75; : Z

: pulse: C2_90 :
 : pulse: C2_90 :
 : pulse: C2_90 :

refocus 112 : 11

0. line ended .0

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Atacuda, Sept. 201

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011100

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

```

3u
| CI_90:ap9 ph2
3u
3u app13
0.71365
3u
3u
| CI_90:ap9 ph2
3u app15 app
3u
| CI_90:ap9 ph2
3u app15 app
3u Eq1:F2
3u Eq2:F1
5000 ph2
1000
lhold 10000 on

```

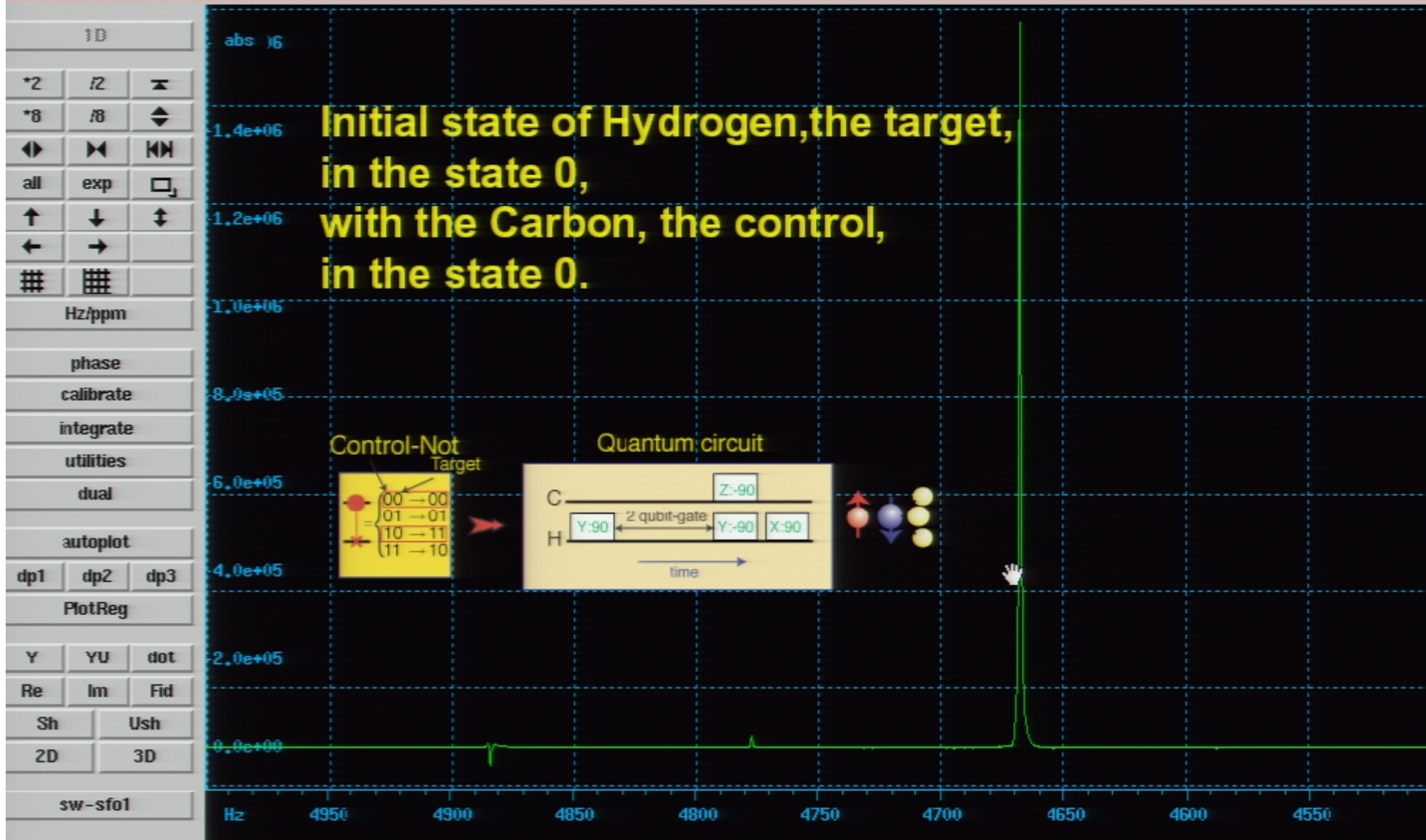
```

3u_
3u_ipp13
0.71365m
8u
8u
(C2_90:sp9_ph19):f1
6u_ipp15_ipp19
8u
(C2_90:sp9_ph20):f1
6u_ipp15_ipp20

```

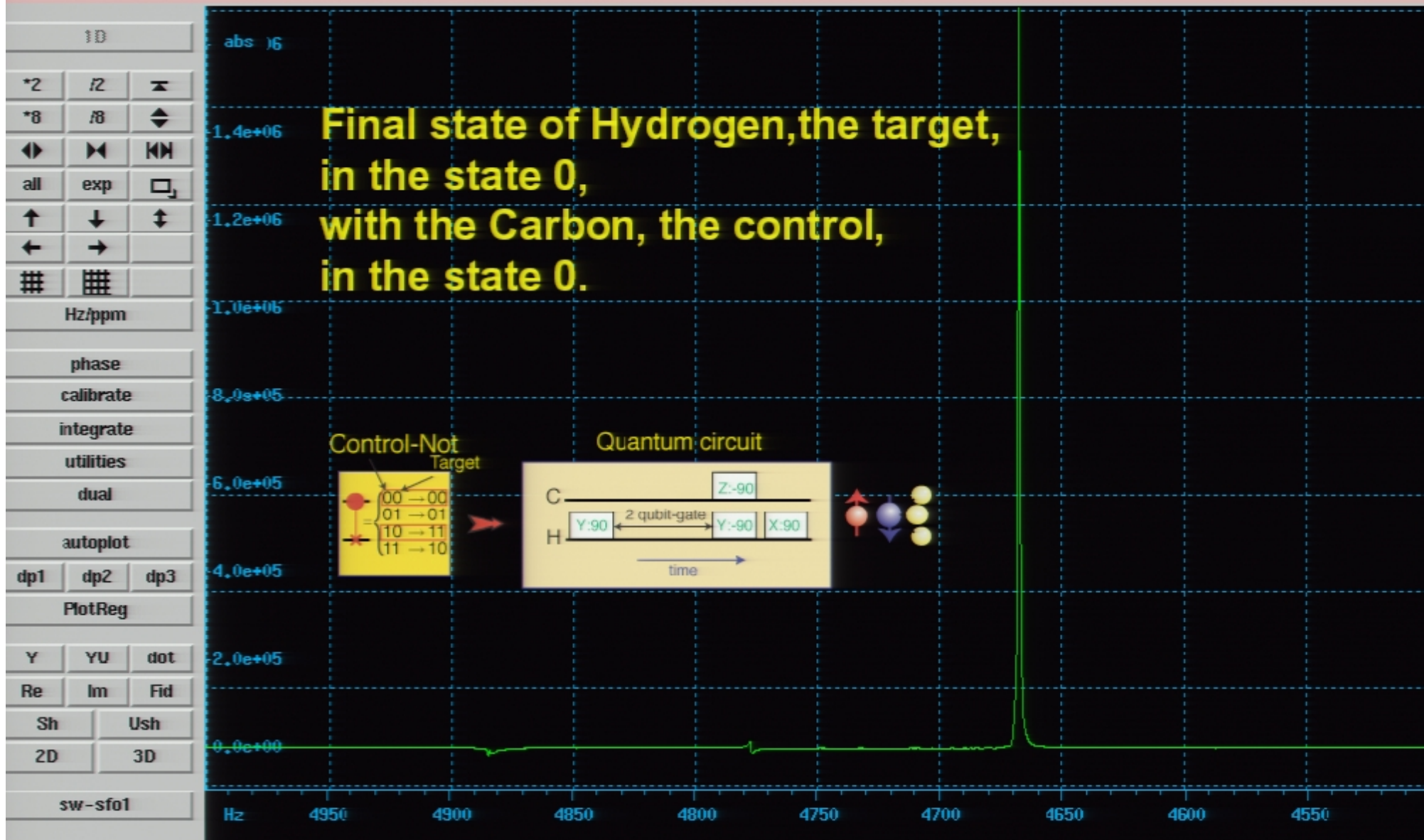
Dataset: < chloroform 10 1 C: laflamme >

Title: pseudopure state carbon ↑



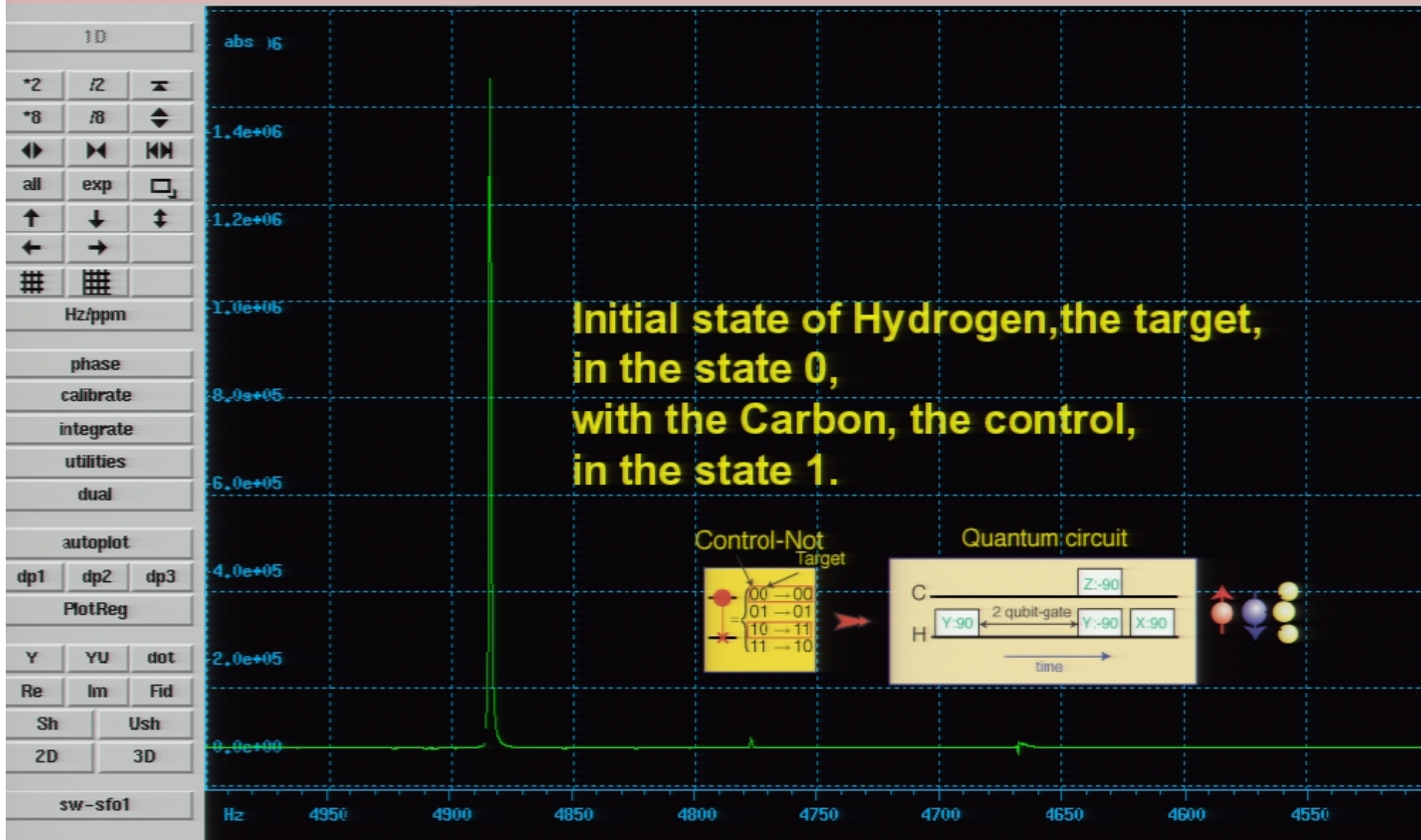
Dataset: < chloroform 11 1 C: laflamme >

Title: pseudopure state plus 1/2J delay carbon ↑



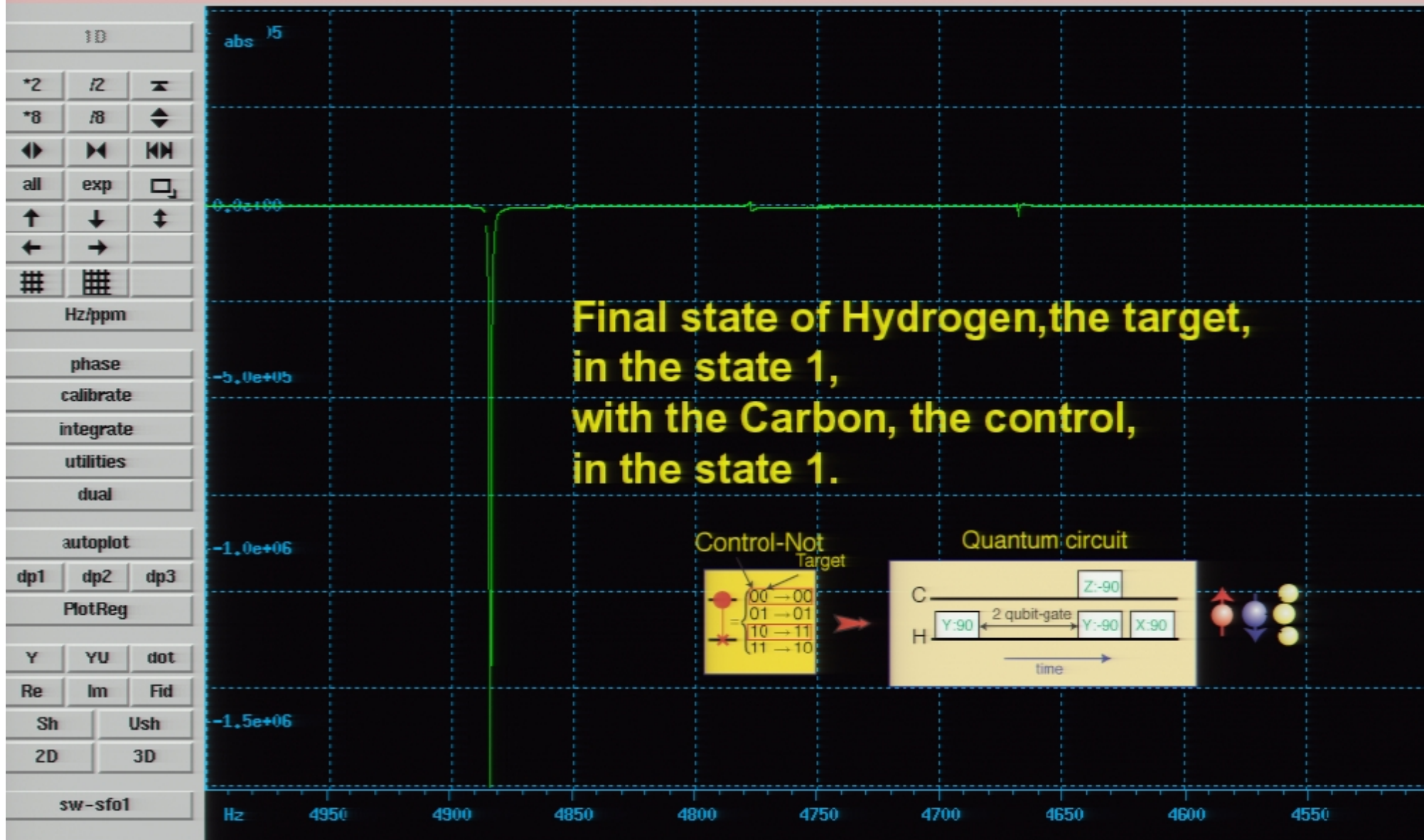
Dataset: < chloroform 12 1 C: laflamme >

Title: pseudopure state carbon ↓



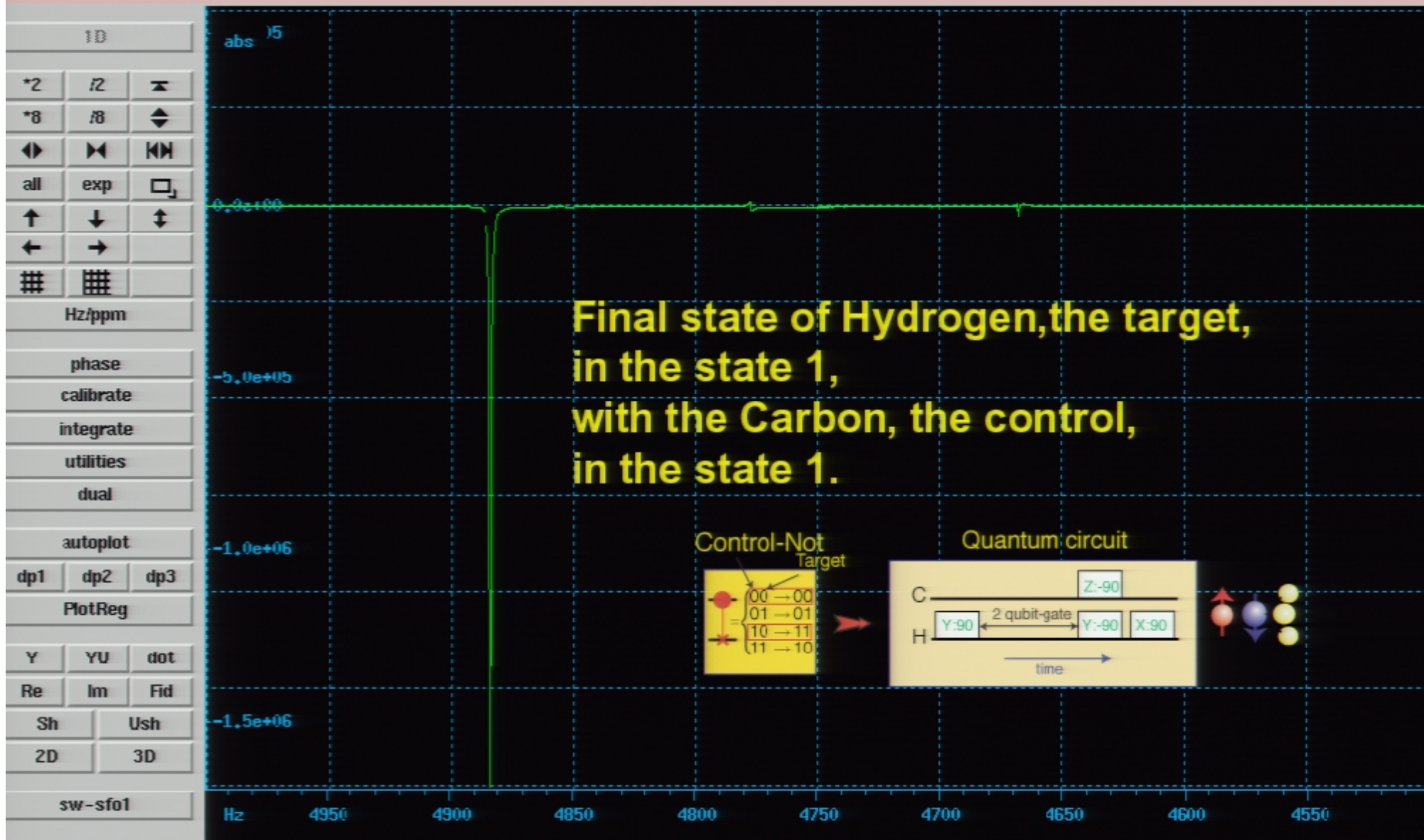
Dataset: < chloroform 13 1 C: laflamme >

Title: pseudopure state plus 1/2J delay carbon ↓

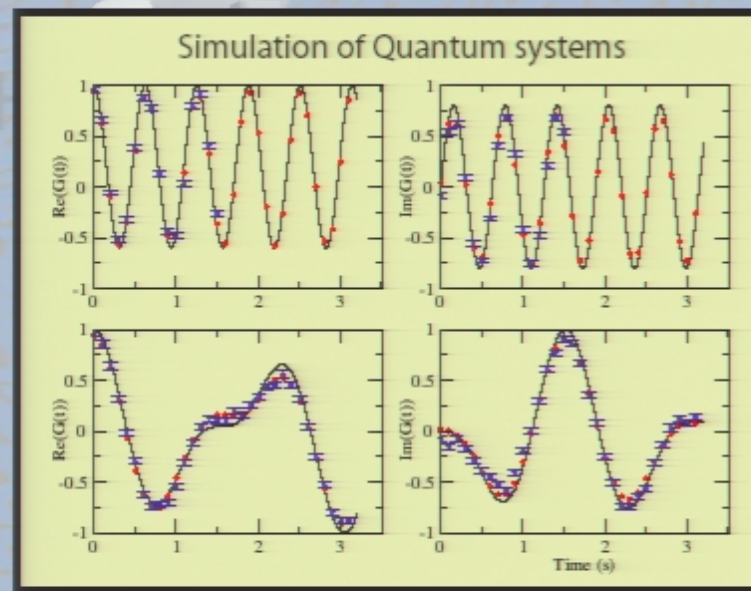
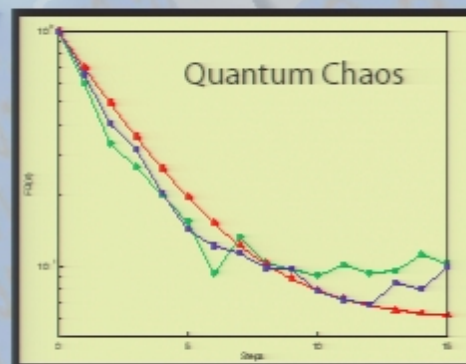
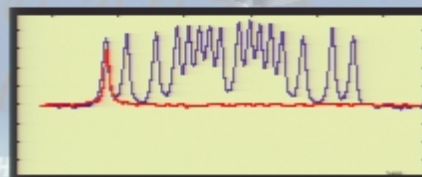
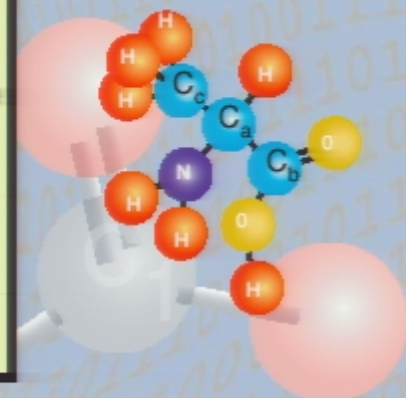
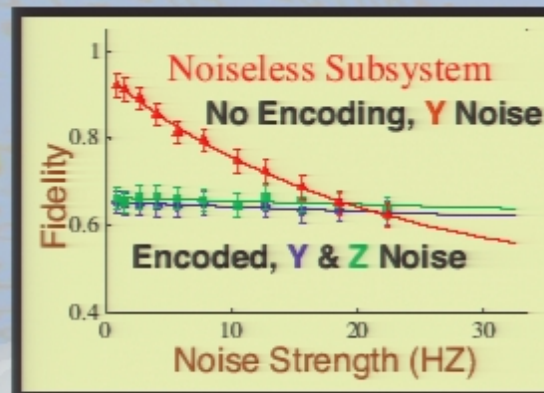
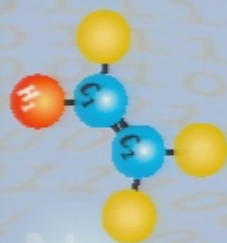
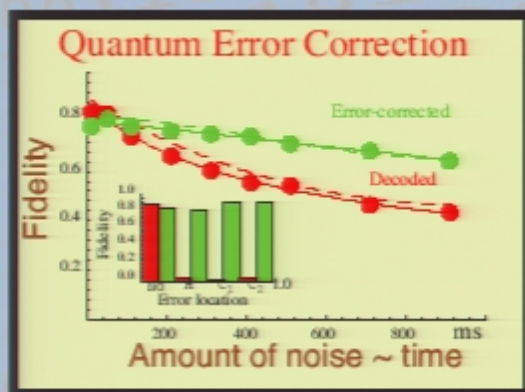


Dataset: < chloroform 13 1 C: laflamme >

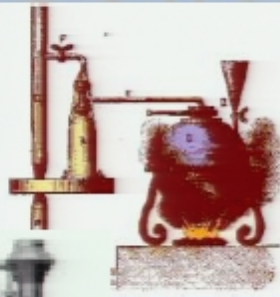
Title: pseudopure state plus 1/2J delay carbon ↓



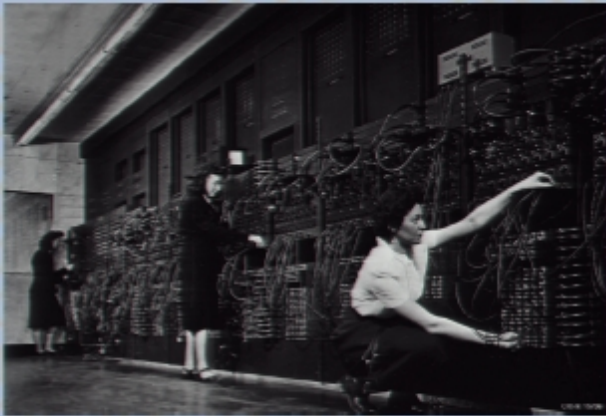
Expt. on small QIP:



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.
- The Institute for Quantum Computing at the University of Waterloo and Perimeter Institute are poised to take advantage of this incredible opportunity.

Sponsors of IQC

Institute for
Quantum
Computing

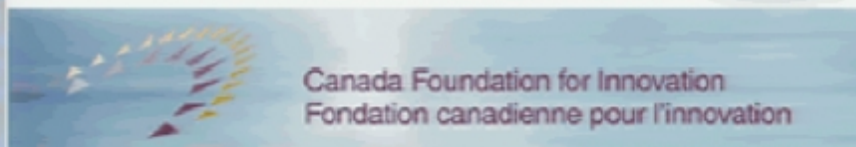


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National
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Agency



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Quantum
Computing

