Quantum Information
NV Centers in Diamond
General Introduction

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April 2011

QIP & QM & NVD Outline

- Interest in Qubits. Why?
- Quantum Information Motivation
  - Qubit vs Bit
  - Sqrt(Not)
- Computer Architecture
- DiVincenzo Criteria
- Violation of Bell's Inequality with NVD
- NVD Ensembles & CPW

Why care about Qubit Research?

Applied:

Quantum System Emulator
- solve molecules
- study fundamental physics

Quantum Computer
- certain parallel processing power

Spinoffs
- ultra low noise amplifiers

Fundamental:

Excellent Quantum Mechanics Test Bed
- Study the scope of the theory of quantum mechanics
- Probe for new phenomena
- Engineer quantum systems with desired properties

Quantum Information

General Introduction

Encoding Information

Quantumly

QuBits
(1 and/or 0)

Classically

Bits
(1 or 0)

Using bits to encode #s. Using those #s to encode letters (each letter corresponds to a number), or
Pictures,
Movies,
Systems, etc.

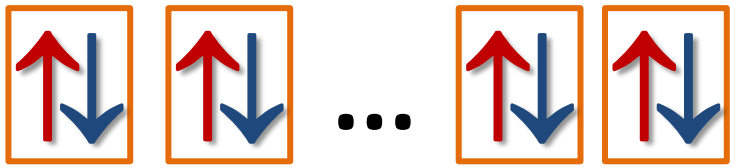
Quantumly

One Quantum N Bit Register

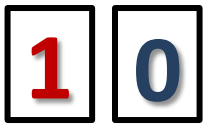
Range: 2^N

Can store 2^N Numbers

To Store N #s => 1 Register



Classically

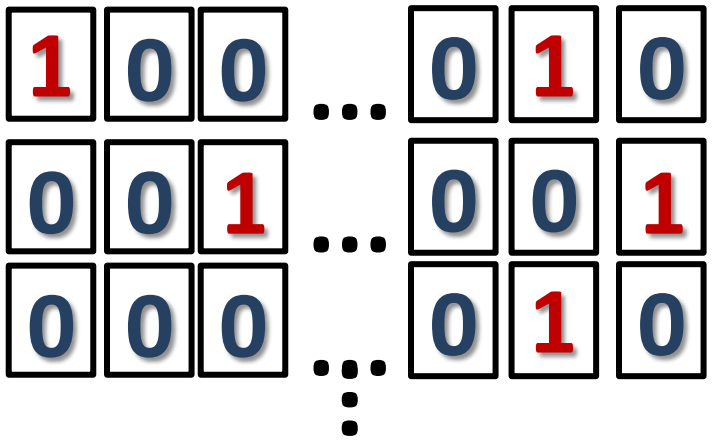


One Classical N Bit Register

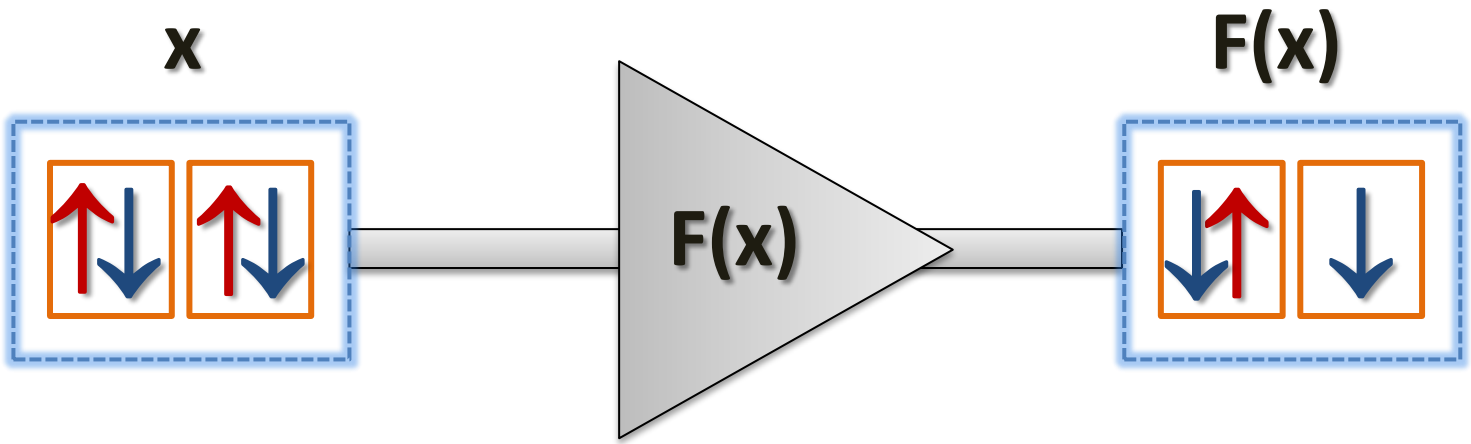
Range: 2^N

Can store 1 Number

To Store N #s => N Registers



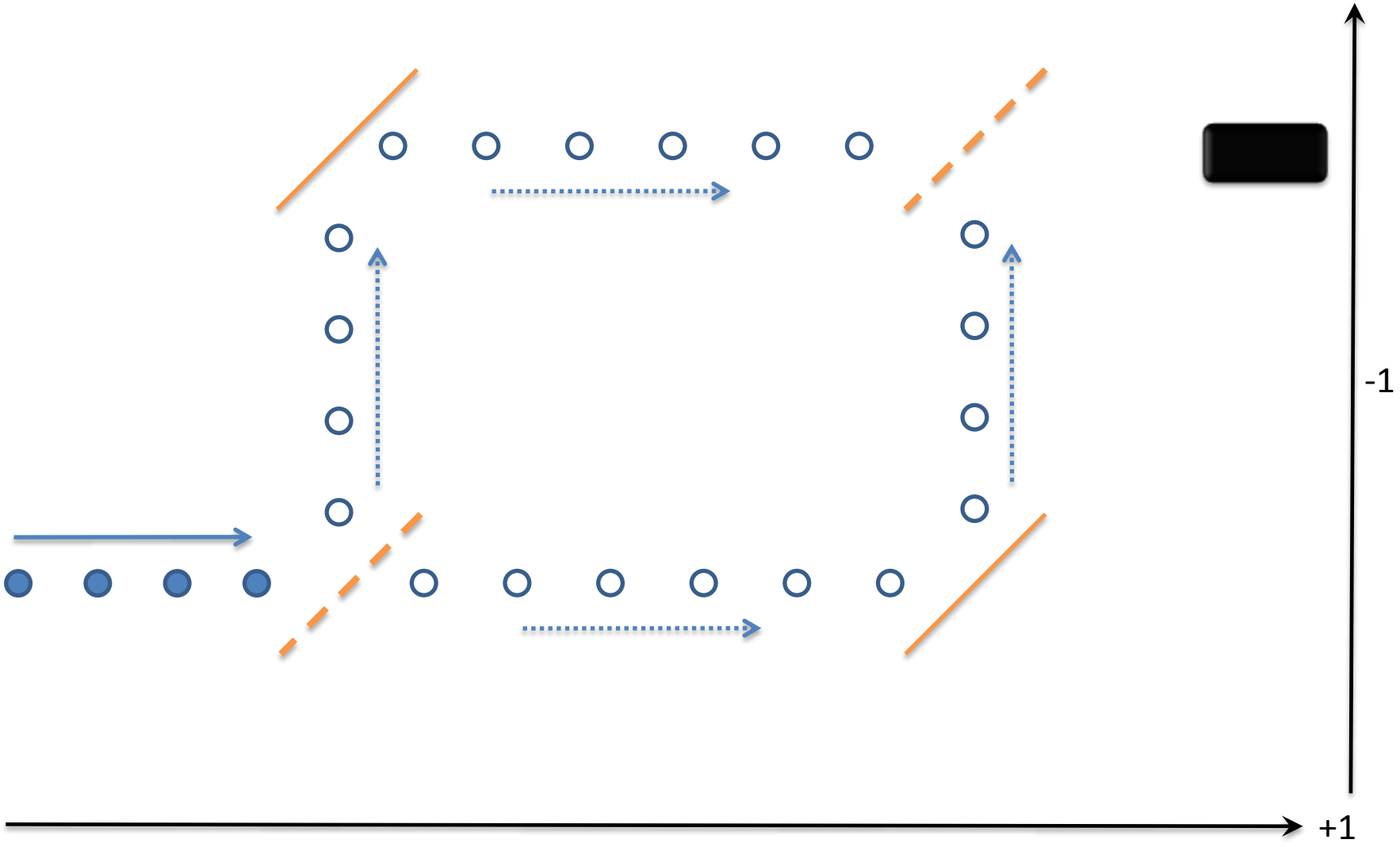
Quantum Algorithms

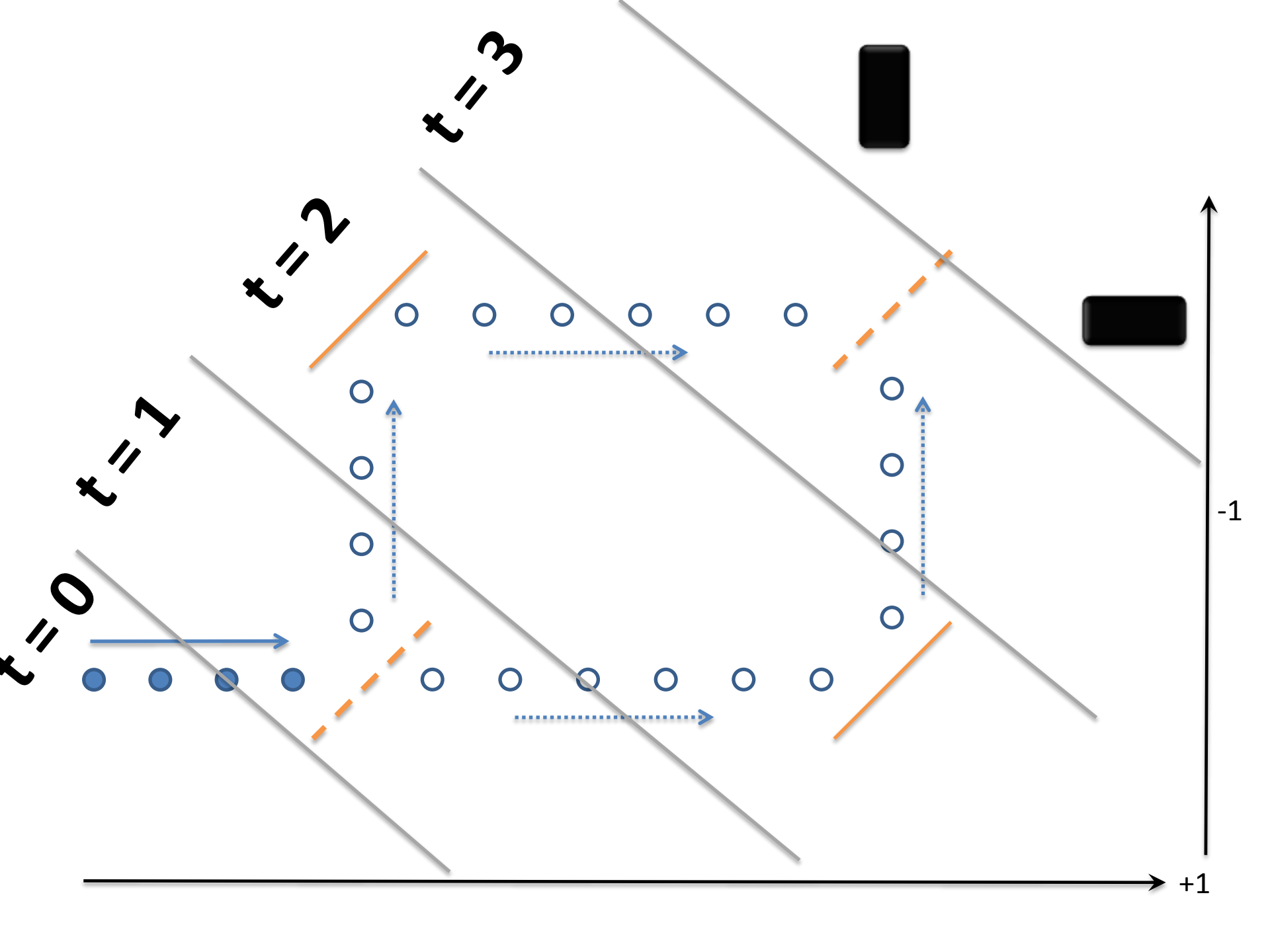


Classically, F(x) would have had to be invoked 2^N number of times.
- Time of execution = $\mathbf{2^N}$ ・RunTime(F(x))

Quantumly, F(x) is invoked only 1 time.
- Time of execution = **1** ・RunTime(F(x))

Consider Qubit…




t=0
t=1
t=2
t=3
-1
+1

Assuming whole # periods of wavelength traveled
(from D. Deutsch Lectures)

t	$\hat{X}$	$\hat{Y}$	$\hat{Z}$
0	σ_x	σ_y	σ_z
beam splitter			

$$\hat{Z}(t+1) = \hat{X}(t)$$
$$\hat{Y}(t+1) = \hat{Y}(t)$$
$$\hat{X}(t+1) = -\hat{Z}(t)$$
$$\hat{1}(t+1) = \hat{1}(t)$$

t	$\hat{X}$	$\hat{Y}$	$\hat{Z}$
0	σ_x	σ_y	σ_z
beam splitter			
1	$-\sigma_z$	σ_y	σ_x

$$\hat{Z}(t+1) = \hat{X}(t)$$

$$\hat{Y}(t+1) = \hat{Y}(t)$$

$$\hat{X}(t+1) = -\hat{Z}(t)$$

$$\hat{I}(t+1) = \hat{I}(t)$$

t	$\hat{X}$	$\hat{Y}$	$\hat{Z}$
0	σ_x	σ_y	σ_z
beam splitter			
1	$-\sigma_z$	σ_y	σ_x
mirrors			

Effective NOT

$$\hat{Z}(t+1) = -\hat{Z}(t)$$
$$\hat{Y}(t+1) = \hat{Y}(t)$$
$$\hat{X}(t+1) = -\hat{X}(t)$$

t	$\hat{X}$	$\hat{Y}$	$\hat{Z}$
0	σ_x	σ_y	σ_z
beam splitter			
1	$-\sigma_z$	σ_y	σ_x
mirrors			
2	σ_z	σ_y	$-\sigma_x$

$$\hat{Z}(t+1) = -\hat{Z}(t)$$

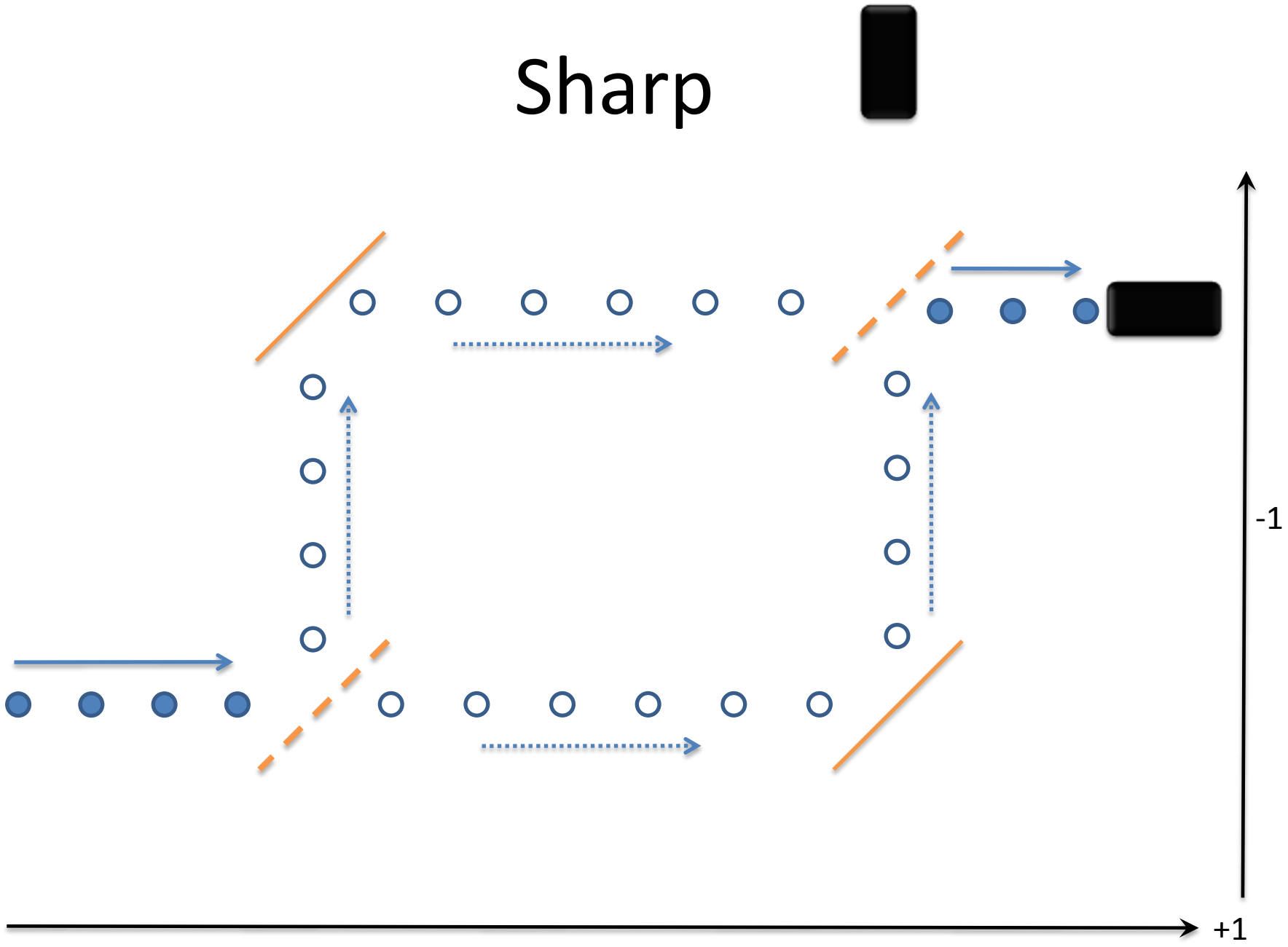
$$\hat{Y}(t+1) = \hat{Y}(t)$$

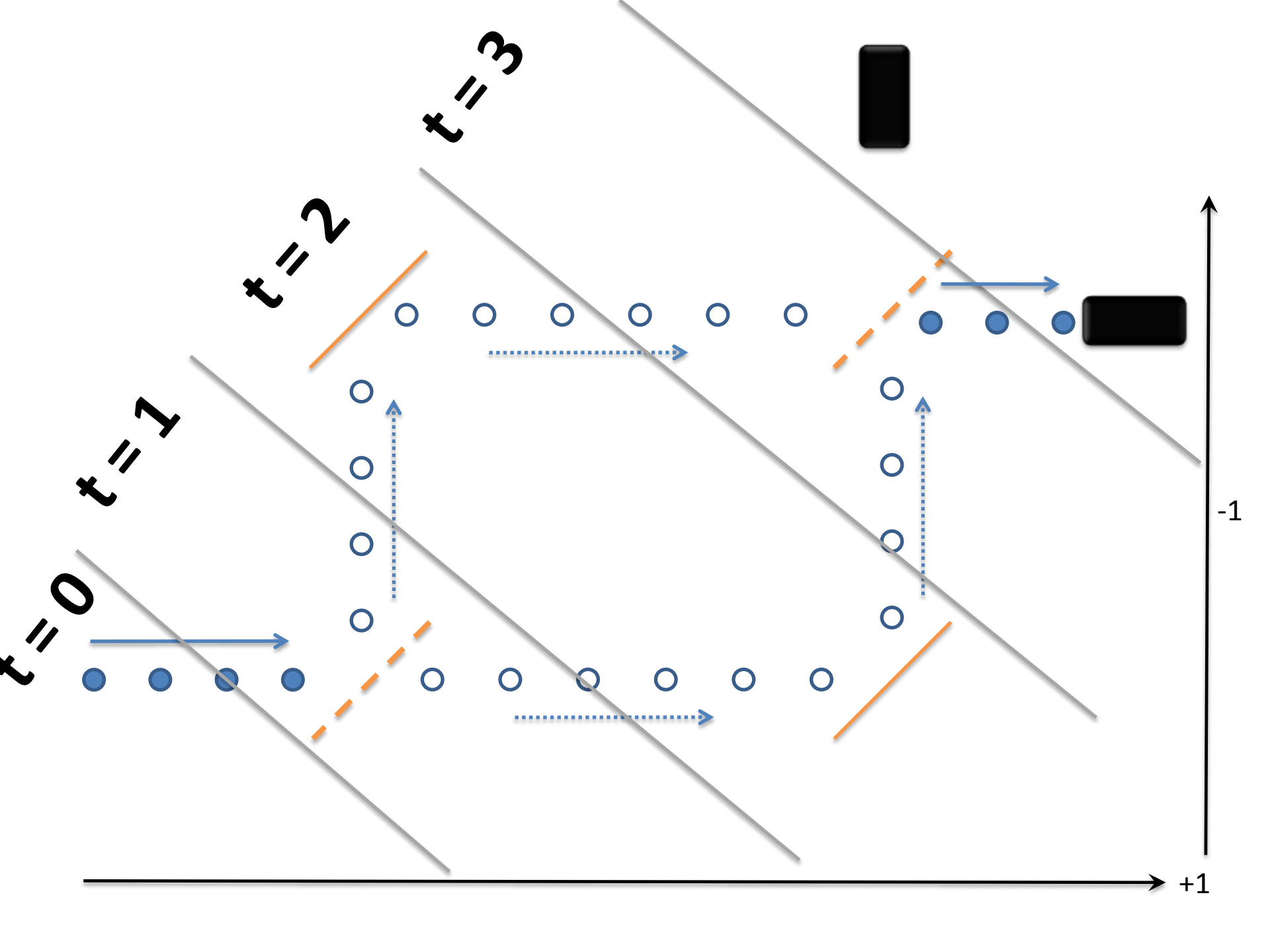
$$\hat{X}(t+1) = -\hat{X}(t)$$

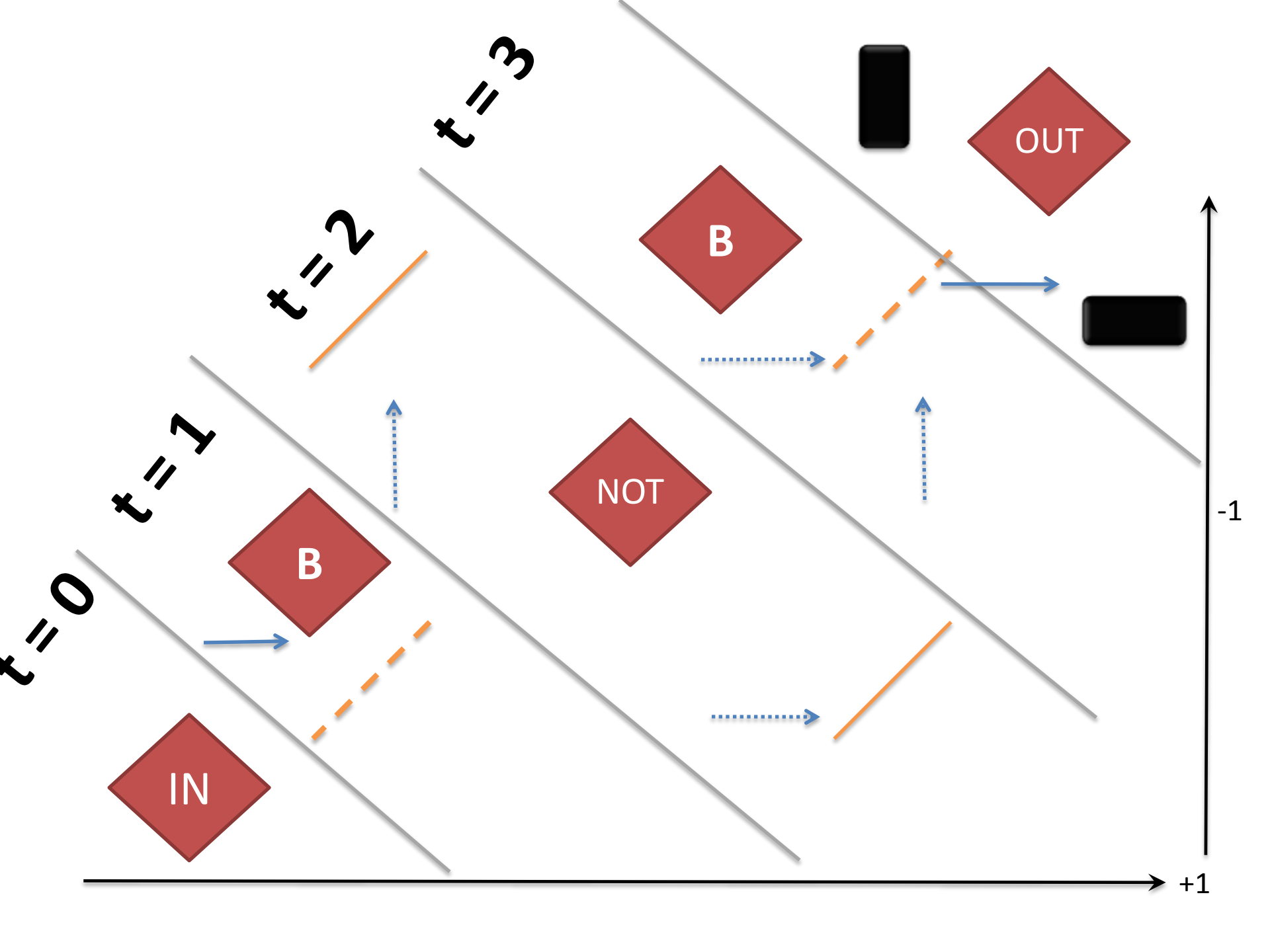
t	$\hat{X}$	$\hat{Y}$	$\hat{Z}$
0	σ_x	σ_y	σ_z
beam splitter			
1	$-\sigma_z$	σ_y	σ_x
mirrors			
2	σ_z	σ_y	$-\sigma_x$
beam splitter			
3	σ_x	σ_y	σ_z

Sharp

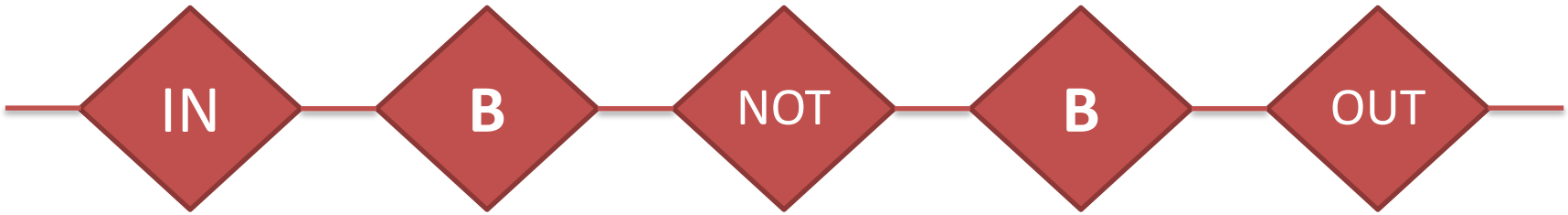
Sharp




t=0
t=1
t=2
t=3
-1
+1


t=0
t=1
t=2
t=3
IN
B
NOT
B
OUT
-1
+1

This is our Operation



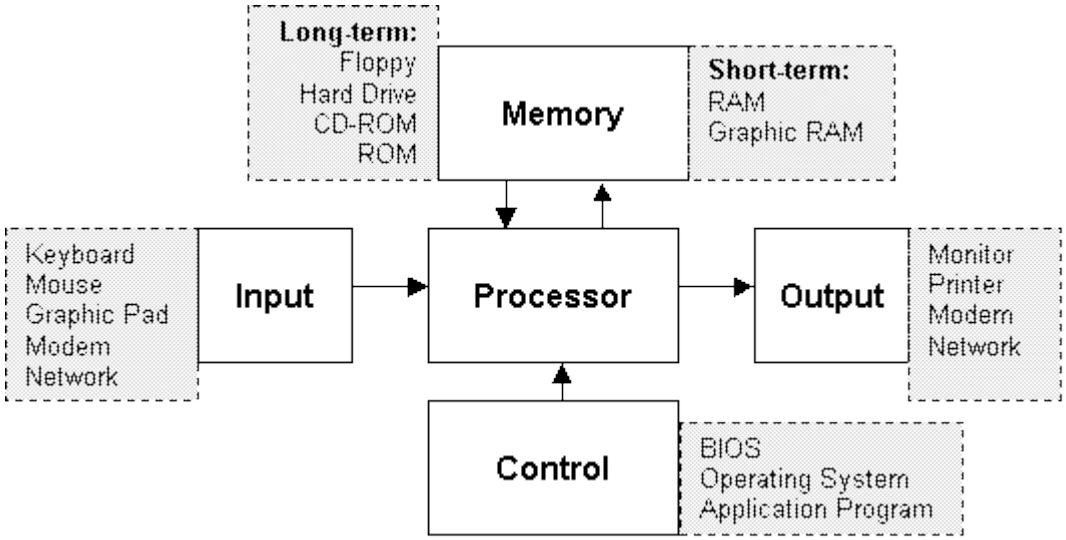
$$B \cdot NOT \cdot B = 1$$

$$B^{-1} = \sqrt{NOT}$$

on 1 bit

Computer Architecture

Digital Computer Organization



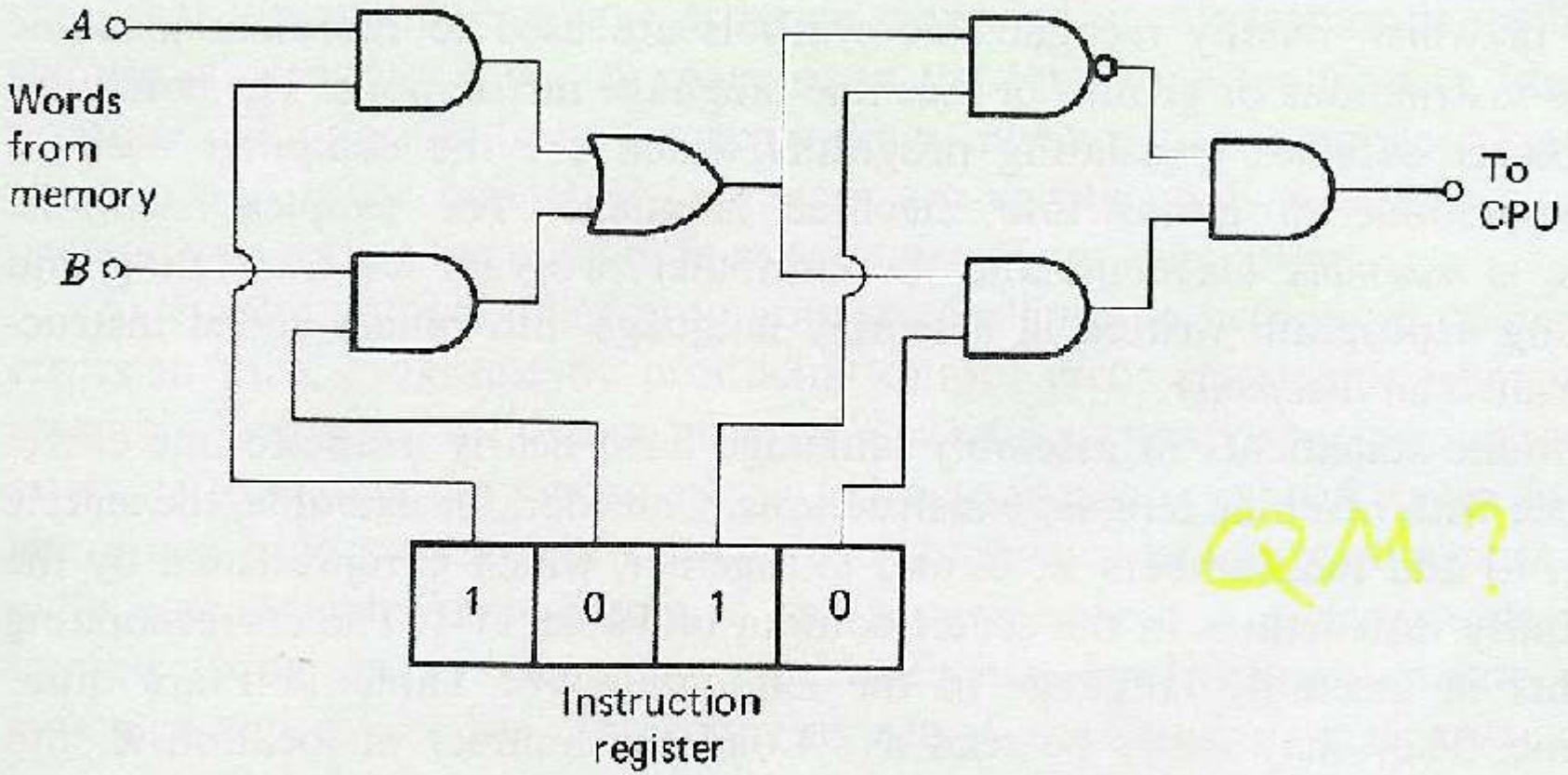


Figure 11-2 Instruction determines path of words through digital computer.

Bit by Bit

Sequential Computing

Memory address	Memory word	Comment
0000	0010	Step 1. Read following word as address.
0001	1110	
0010	0100	Step 2. Read data word and store in CPU.
0011	0010	Step 3. Read following word as address.
0100	1111	
0101	0110	Step 4. Add
0110	1000	Steps 5 and 6. Store
0111	0000	Halt
1000		
1001		
1010		
1011		
1100		
1101		
1110	0100	Data word
1111	0001	Data word

Figure 11-6 Program to add 0100 and 0001.

Table 11-2 4-Bit instruction set

Instruction	Interpretation
0010	Read the contents of next memory word and interpret as a data memory address.
0100	Read the contents of the addressed data word, interpret as binary data, and store in the CPU.
0110	Add the contents of addressed data memory word to data word stored in CPU.
1000	Store data word in CPU at memory word addressed by data memory address.
1001	Read data word in the I/O register and store in CPU.
1010	Read data word in CPU and store in the I/O register.
1100	Complement data word stored in CPU.
0000	Halt.

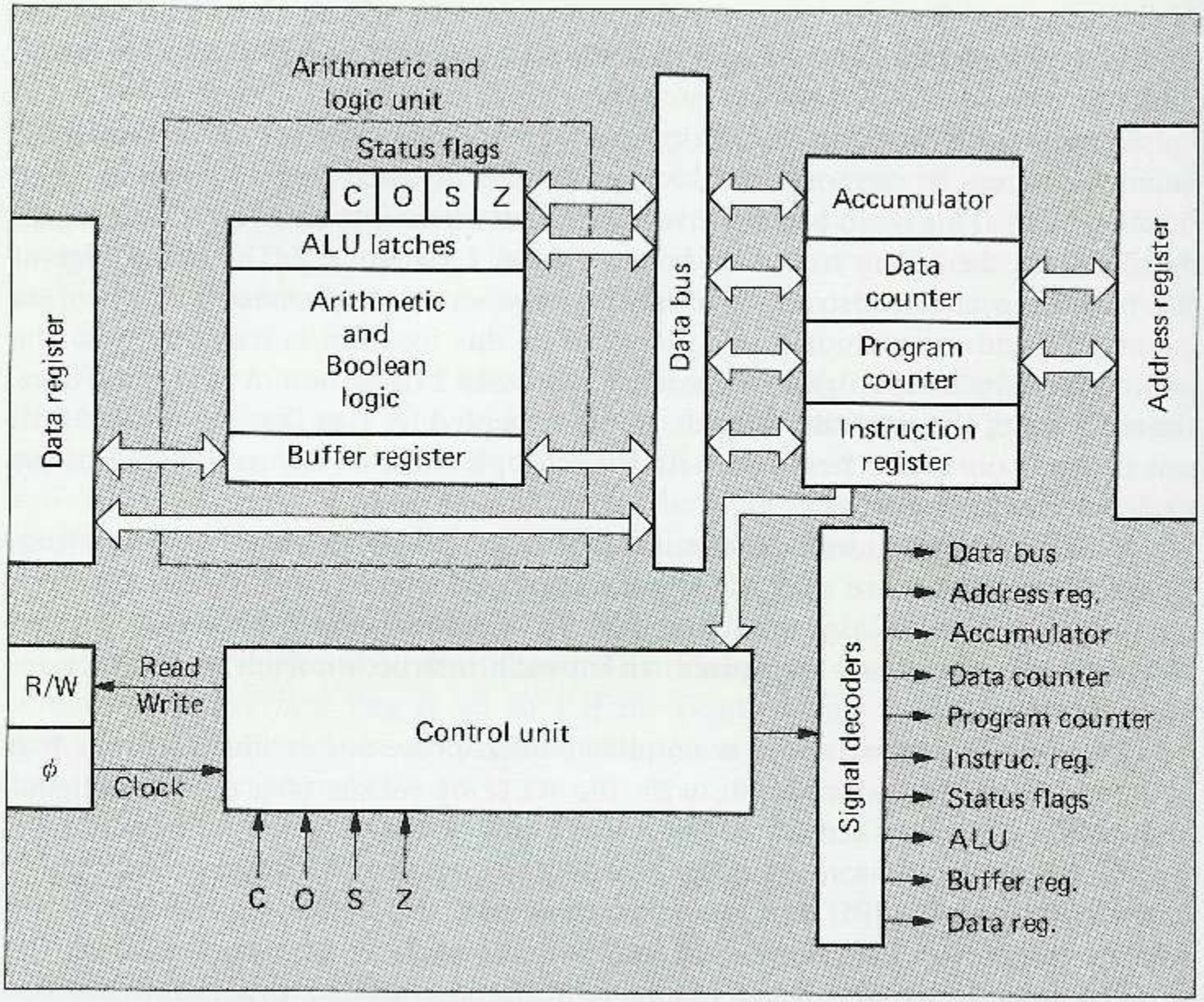
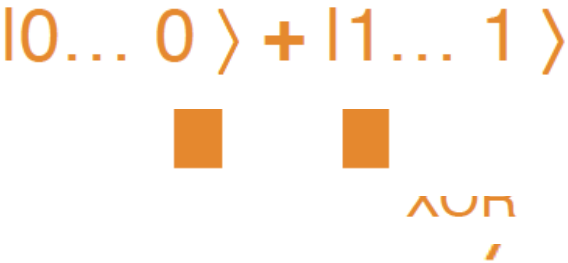


Figure 11-8 Microprocessor chip organization.

DiVincenzo Criteria

- 5 criteria to build operational quantum computer
  - Well defined Qubits
  - Initiation into pure state
  - Universal set of Quantum Gates
  - Qubit-Specific Measurement
  - Long Coherence Times



- 2 additional criteria for quantum communication
  - Interconvert stationary and flying Qubits
    - E.g. Repeater stations
  - Transmit flying Qubits between distant locations
    - E.g. Error correction

NV Diamond Qubit

Table 1. *Status of NV diamond relative to DiVincenzo criteria.*

	Criteria	**Low temp**	**Room temp**
1	Well-defined qubits	✓	✓
2	Initialization to a pure state	✓	✓
3	Universal set of quantum gates	✓	✓
4	Qubit-specific measurement	✓	Progressing well
5	Long coherence times	✓	✓
6	Interconvert stationary and flying qubits	Progressing well	Maybe
7	Transmit flying qubits to distant locations	Progressing well	Progressing well

Violation of Bell's Inequality Using NV Diamond

Bell Inequality

- What is it?
  - A means of testing quantum mechanics
- Temporal versus Spatial inequalities
- Temporal Bell Inequality (TBI) based on two assumptions
  - Reality
    - The state of a physical system is always well defined
  - Stationarity
    - Conditional Probability of system to change to depends only on the time difference between measurements

Temporal Inequality

- Conditional Probability
  - $Q_{ij}(t_1,t_2)$
- Bounds on strength of temporal correlations:

$$Q_{ii}(0,2t) - Q_{ii}^2(0,t) \geq 0$$

- Can be violated by quantum mechanical dynamics (i.e. Rabi Oscillations).
  - This will violate the realist description of the physical dynamics and motivate the inherent truth of quantum mechanics

Set up for the diamond

- NV^- vs NV^0 centre
  - 30% of the time in NV^0 state
    - Due to two photon ionization
  - NV^0 state hinders measurements to see Rabi Oscillations necessary to violate TBI
  - Flash green light to put into excited NV^- state

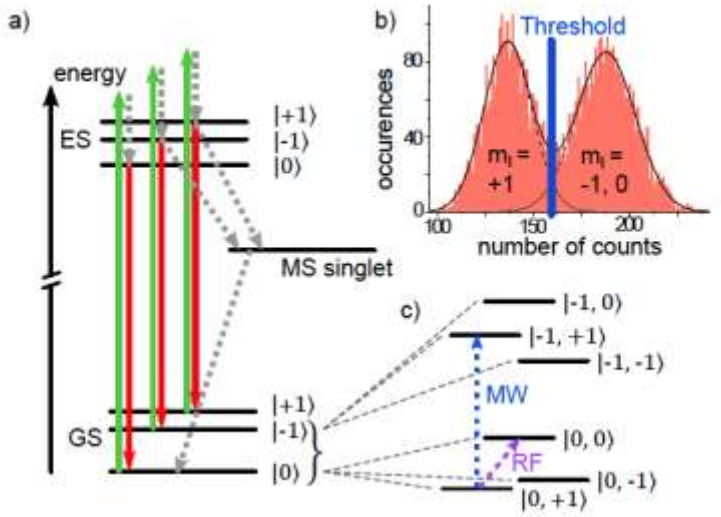
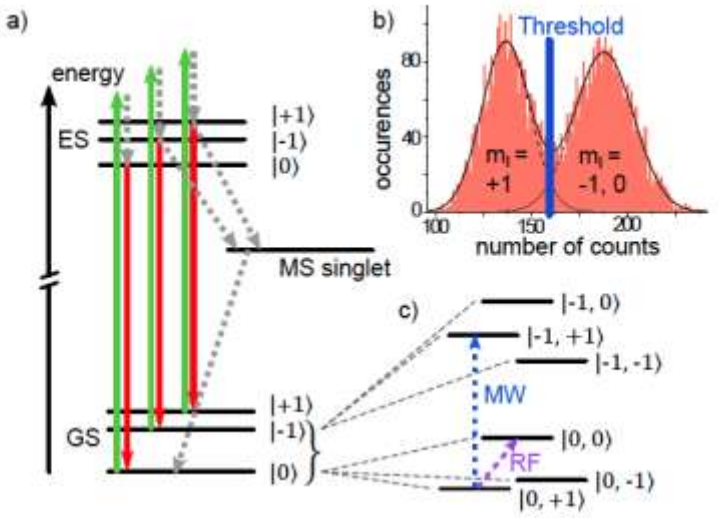


FIG. 1: a) Energy level scheme of the NV^- defect in a small magnetic field. Optical transitions occur between ground state (GS) and excited state (ES) (vertical arrows), dotted lines (gray) indicate radiationless decays. Line thickness corresponds to transition rates. b) Histogram of many subsequent QND measurements of the nitrogen nuclear spin. Low fluorescence level indicates that the MW π pulse was successful, i.e. that the nuclear spin state is $m_I = +1$. c) Magnification of the $m_S = 0, -1$ levels including hyperfine splitting due to the ^{14}N nuclear spin (states are denoted as $|m_S, m_I\rangle$). The dotted (blue) arrow illustrates the nuclear spin selective MW π pulse, the dashed (purple) arrow the nuclear spin transition driven by RF pulses.

Set up for the diamond

- Electron Spin destroyed during this process
  - Nuclear Spin made robust with strong magnetic field (B=0.6T)
  - Mapped onto electron state with CNOT-Gate
  - Make quantum non-demolition (QND) measurement of Nuclear Spin:



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Set up for the diamond

- Zero-Phonon Line (ZPL)
  - NV^0 is 575nm
  - NV^- is 637nm
    - Wavelengths significantly greater than 575 will not induce fluorescence from NV^0.
    - Illuminate with orange light (600nm)
- Low power excitation
  - Ionization rate of NV^- decreases quadratically with power
  - Fluorescence decreases linearly
  - / n NV^- before it becomes i

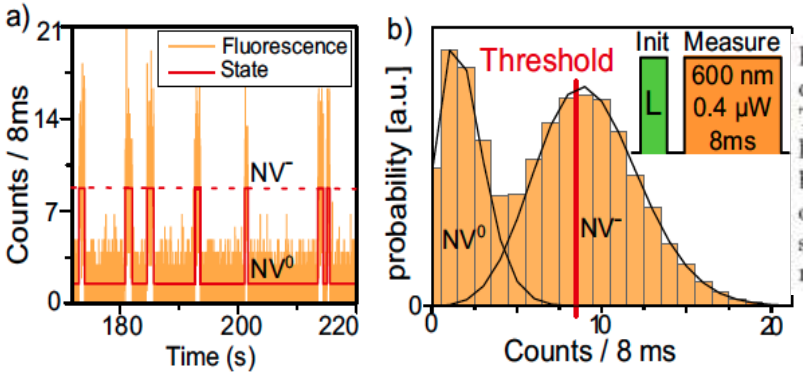
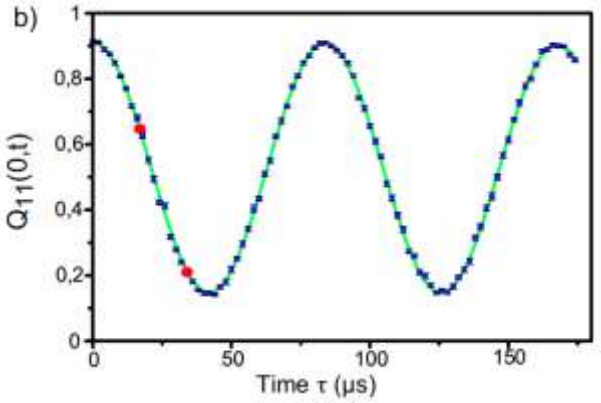


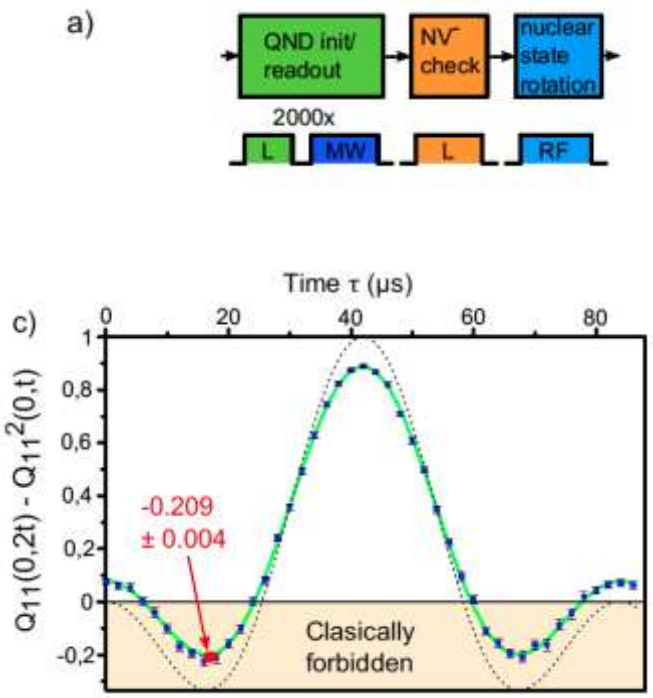
FIG. 2: a) Timetrace of the fluorescence of the NV under cw illumination with 600nm, 0.4μW laser light (orange line). The red line shows the most likely fluorescence level. The lifetime of NV^- during orange illumination is around 600 ms. b) Histogram of measurement results showing the distribution of counted photons during orange illumination for the inset sequence: Green pulses "reset" the NV and 8 ms orange pulses measure the charge state.

Resulting Measurements

- After choosing only NV^- centres
  - Using the measurement sequence:
  - Rabi Oscillations occur:



  - Giving the resulting TBI graph



VBI Conclusion

- Violated TBI!
  - Over 50 standard deviations
  - Dynamics of single nuclear spin cannot be described by “realist theory”
    - Quantum Mechanics stands strong!

Future work

- 2 nuclear spin entanglement
  - contextuality of quantum mechanics can be tested
    - Non-contextuality: the property that any measurement has a value which is independent of other compatible measurements being made at the same time.
- Quantum Information and Processing
  - Refining stability of NV^-

References

- G. Waldherr, P. Neumann, S. F. Huelga, F. Jelezko, J. Wrachtrup, arXiv:1103.4949v1 [quant-ph]
  - Violation of Temporal Bell Inequality for single spins in solid by over 50 standard deviations.
- P. Hemmer, J. Wrachtrup, F. Jelezko, and S. Prawer, SPIE Newsroom, 10.1117/2.1200711.0941
  - Diamonds for Scalable Quantum Information Systems
- G. Kirchmair, F. Zahringer, R. Gerritsma, M. Kleinmann, O. Guhne, A. Cabello, R. Blatt, and C. F. Roos, Nature 460, 494 (2009).
  - State-independent Experimental test of quantum contextuality

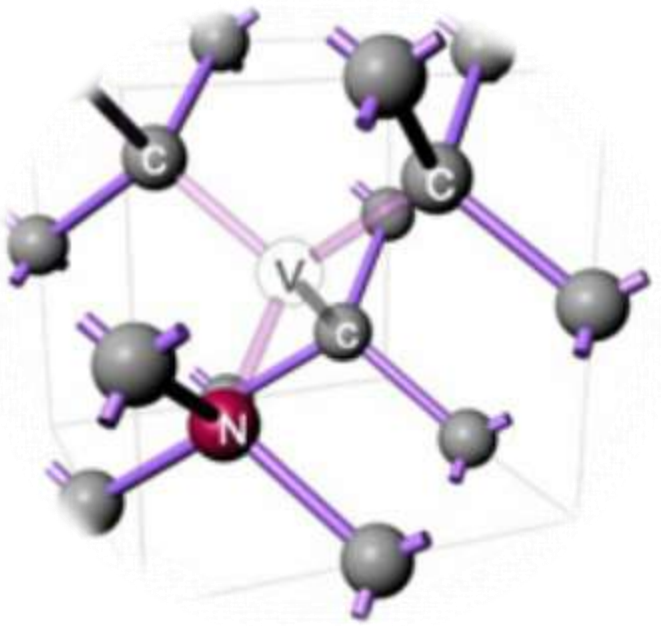
Strong Coupling of a Spin Ensemble to a Superconducting Resonator

Color centers in solids (NV^-)

Show astonishingly long coherence times even at room temperature ~ 2ms

- Enable: Quantum memories

Provide coherent bridges between electron spin resonances (ESR) in the GHz range and optical photons suitable for long-distance transfer



Slower quantum state manipulation

- Solution: Hybrid System

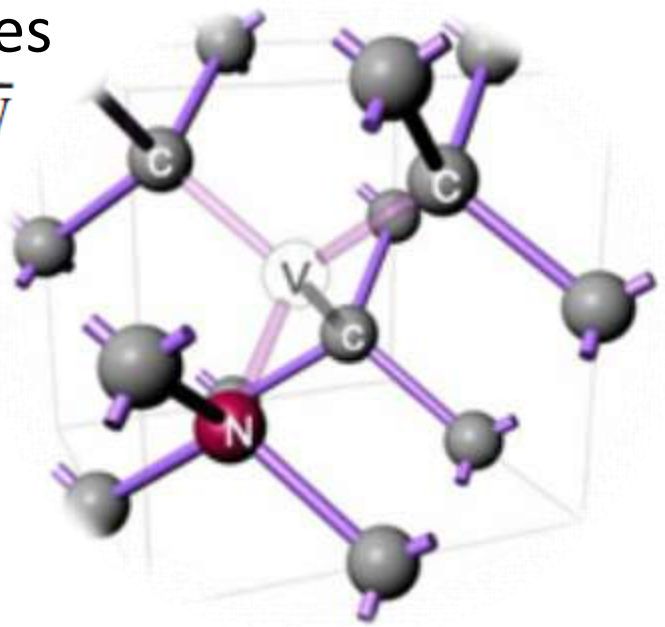
Atomic Ensembles

Issue:

Coupling between a single spin and the electro-magnetic feld is typically very weak

Solution:

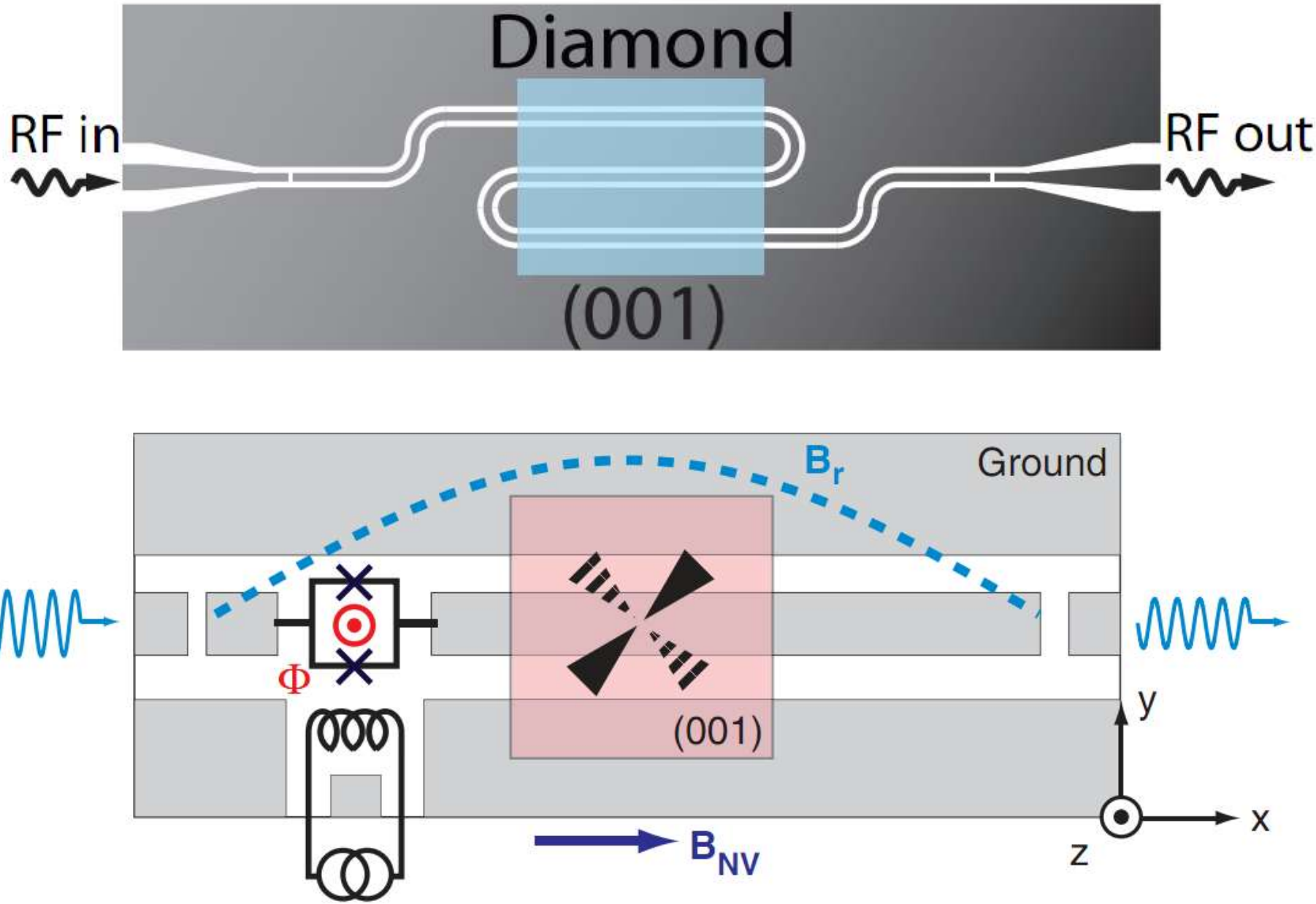
•writing single excitations into ensembles of N spins, it is enhanced by a factor $\sqrt{N}$



Still Need:

$$g\sqrt{N} \gg \kappa, \gamma$$

Overcome *resonator* and *emitter* damping rates


Diamond
RF in
RF out
(001)
B_r
Ground
Φ
(001)
y
x
z
B_{NV}

Some Numbers

Zero Field Splitting:	~ 2.87 GHz
NV Center Population:	~ 10^{12}
Collective Coupling Constant g:	~ 11 MHz
Resonator Quality Factor Q:	~ 2×10^{4}
Diamond Dimensions:	~ 3x3x0.5 mm
Operational Temperature:	~ 40 mK
Diamond Type:	High Pressure/Temp

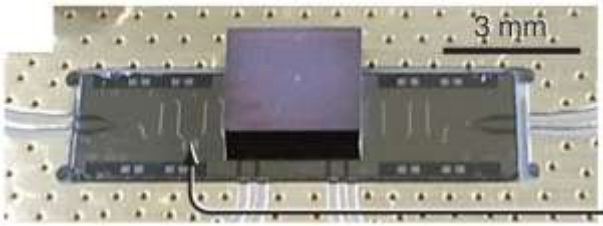
Conclusion Spin Ensemble Coupling

- Strong coupling between an ensemble of nitrogen-vacancy center electron spins in diamond and a superconducting microwave coplanar waveguide resonator
  - However, resonator and spin linewidths need 1 order of magnitude reduction to implement a quantum memory

- Observed scaling of the collective coupling strength with $\sqrt{N}$

- measure hyperfine coupling to C13 nuclear spins
  - first step towards a nuclear ensemble quantum memory

- measure the *relaxation time* T1 of the NV center at millikelvin temperatures in a non-destructive way



PRL 105, 140502 (2010) Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS week ending 1 OCTOBER 2010

Strong Coupling of a Spin Ensemble to a Superconducting Resonator

Y. Kubo,[1] F. R. Ong,[1] P. Bertet,[1] D. Vion,[1] V. Jacques,[2] D. Zheng,[2] A. Dréau,[2] J.-F. Roch,[2] A. Auffeves,[3] F. Jelezko,[4] J. Wrachtrup,[4] M. F. Barthe,[5] P. Bergonzo,[6] and D. Esteve[1]

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We report the realization of a quantum circuit in which an ensemble of electronic spins is coupled to a frequency tunable superconducting resonator. The spins are nitrogen-vacancy centers in a diamond crystal. The achievement of strong coupling is manifested by the appearance of a vacuum Rabi splitting in the transmission spectrum of the resonator when its frequency is tuned through the nitrogen-vacancy center electron spin resonance.

DOI: 10.1103/PhysRevLett.105.140502 PACS numbers: 03.67.Lx, 42.50.Ct, 42.50.Pq, 85.25.Cp

Cavity QED with magnetically coupled collective spin states

R. Amsüss,[1] Ch. Koller,[1,2] T. Nöbauer,[1] S. Putz,[1] S. Rotter,[3] K. Sandner,[4] S. Schneider,[1] M. Schramböck,[1,2] G. Steinhauser,[1] H. Ritsch,[4] J. Schmiedmayer,[1] and J. Majer[1,2,*]

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(Dated: March 8, 2011)

We report strong coupling between an ensemble of nitrogen-vacancy center electron spins in diamond and a superconducting microwave coplanar waveguide resonator. The characteristic scaling of the collective coupling strength with the square root of the number of emitters is observed directly. Additionally, we measure hyperfine coupling to ^{13}C nuclear spins, which is a first step towards a nuclear ensemble quantum memory. Using the dispersive shift of the cavity resonance frequency, we measure the relaxation time T_1 of the NV center at millikelvin temperatures in a non-destructive way.

PACS numbers: 03.67.-a,42.50.Pq,61.72.jn,76.30.-v