Capri Spring School 2024

EXPERIMENTAL IMPLEMENTATION OF NON-UNITARY OPERATIONS IN QUANTUM SUPERCONDUCTING CIRCUITS

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Anacapri, April 15, 2024

OUTLINE:

Introduction: what are non-unitary operations and why are we interested in them? Why many-body physics?

Superconducting quantum circuits as many body systems

Transmon and fluxonium synthetic atoms as qubits

Readout of superconducting qubits as entropy-removal mechanism

Quantum limited amplification chain of measurement

Quantum error correction and fault-tolerant quantum computation

REFERENCES

MD and Schoelkopf, Science (2013) doi: 10.1126/science.1231930

Roy and MD, CRAS Physics (2017) arXiv:1605.00539v2

Vool and MD, IEEE Circuit Theory and Application 2017 doi.org/10.1002/cta.2359

Blais, Girvin and Oliver, Nature Physics **16**, pp. 247–256, (2020)

Campagne, Eickbusch, Touzard *et al*. & MD, Nature **584**, pages 368–372 (2020)

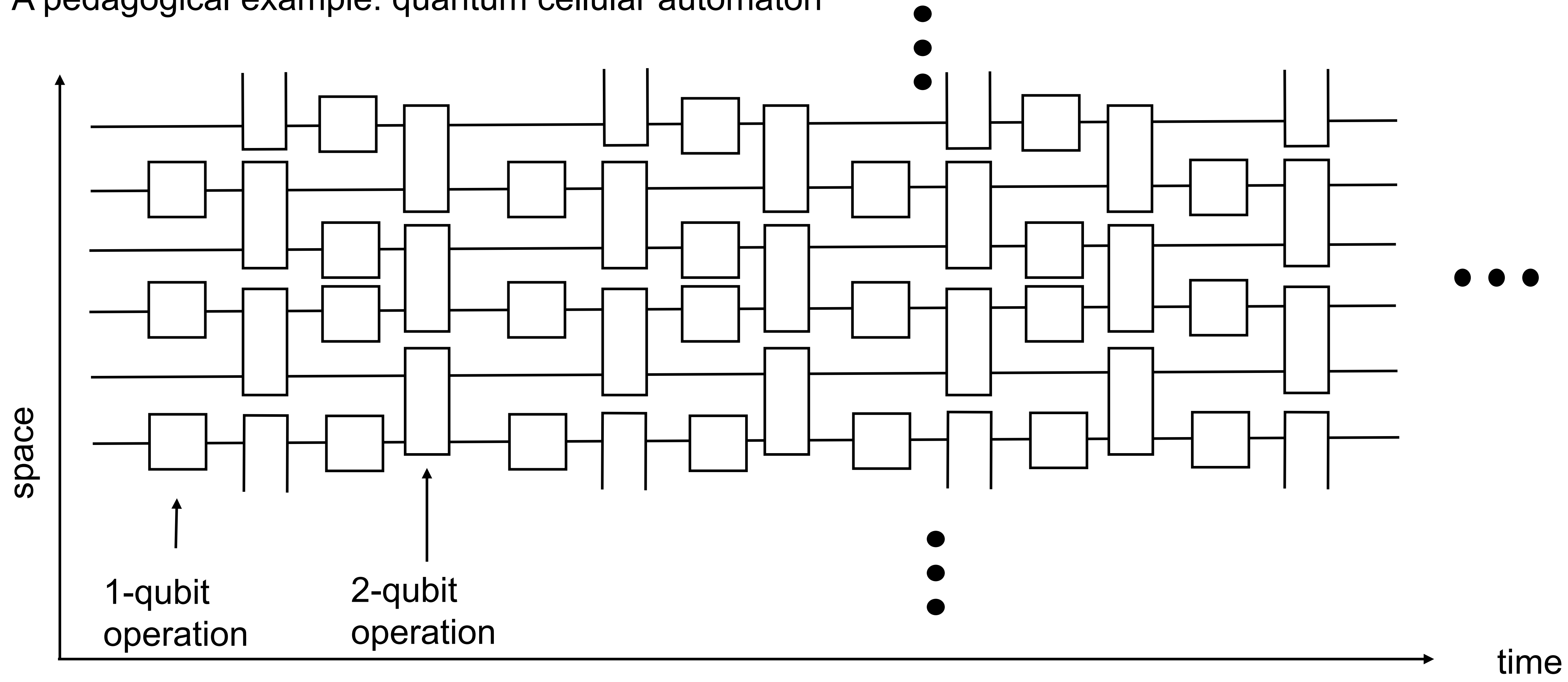
Eickbusch *et al*. & MD, Nature Phys. **18**, pp. 1464–1469 (2022)

Sivak *et al*., & MD, PRX Phys. Rev. X **12**, 011059 (2022)

Sivak *et al*.& MD, Nature **616**, pp. 50–55 (2023)

QUANTUM INFORMATION PROCESSORS AND QUANTUM MANY-BODY PHYSICS

A pedagogical example: quantum cellular automaton



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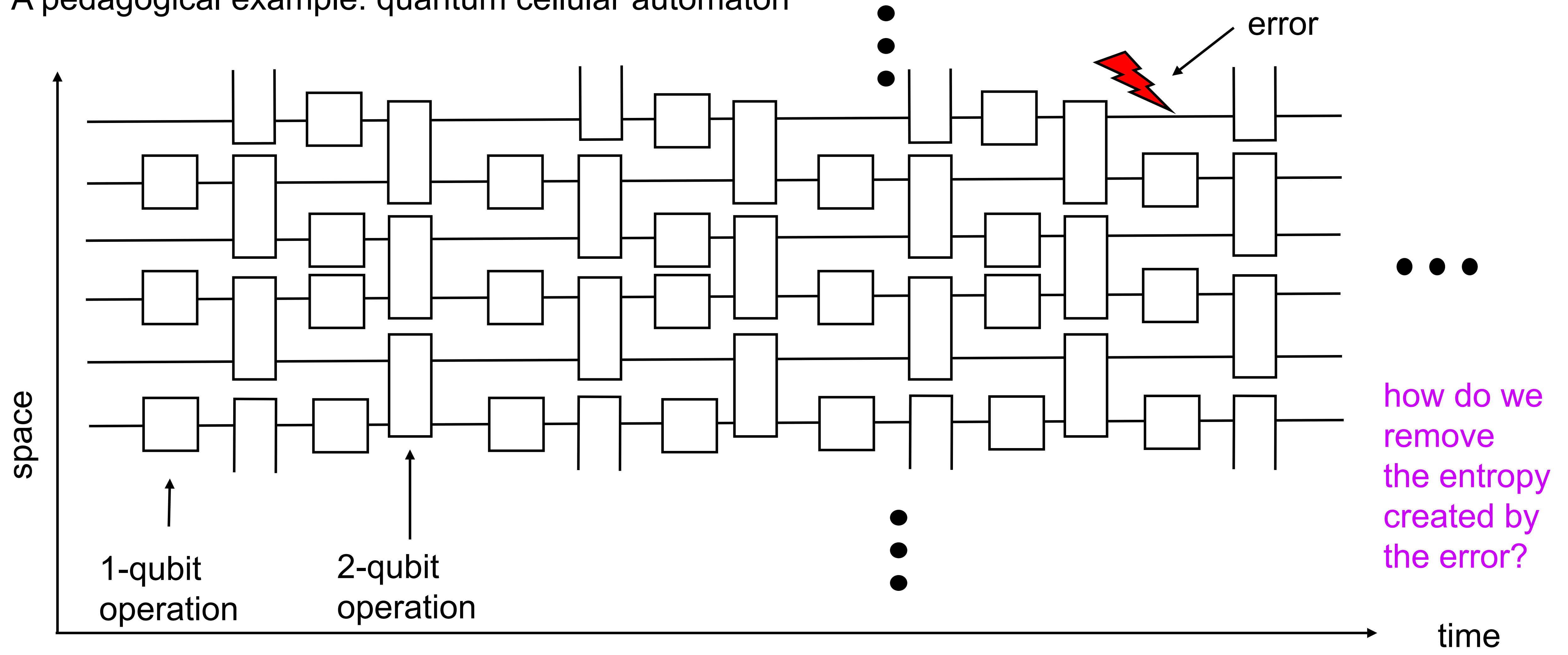
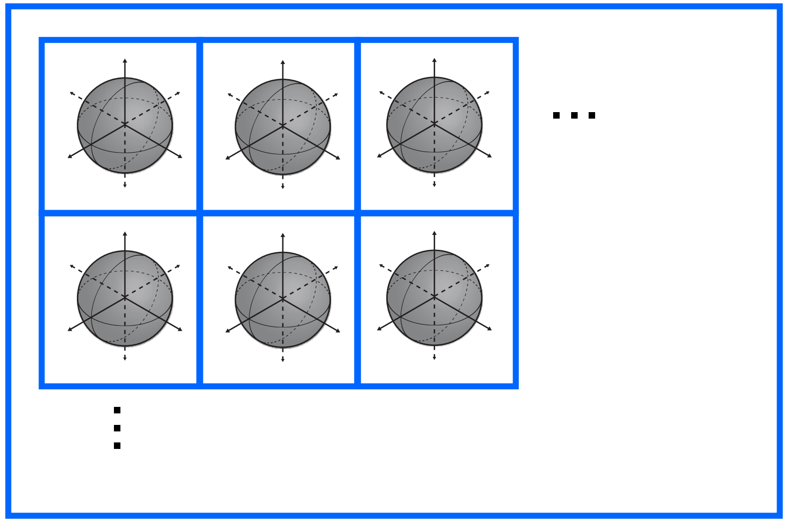


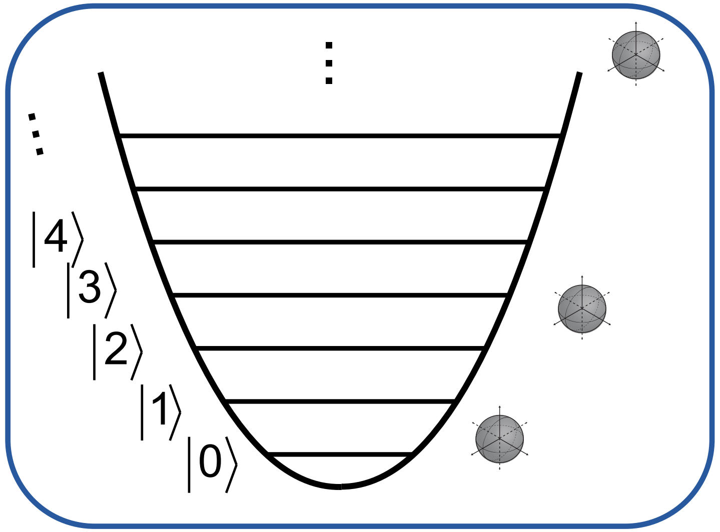
TWO CLASSES OF QUANTUM MANY-BODY PHYSICS

“Discrete” variable



Register of n physical qubits provides large Hilbert space with dimension $N = 2^n$.

“Continuous” variable

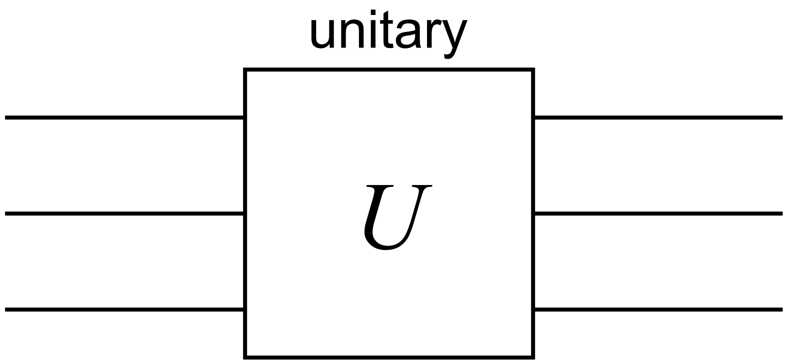


Oscillator states up to $|N>$ provides large Hilbert space equivalent to that of a register of $\mathrm{Log}_2\, N$ qubits.

spin ½ - like excitations: bounded Hilbert space

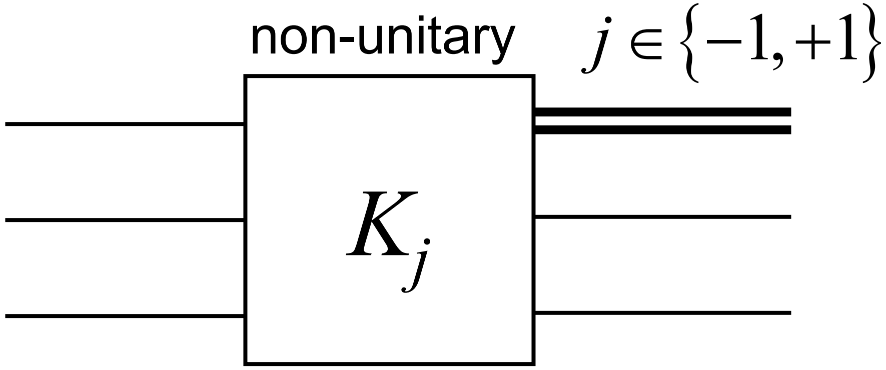
bosonic excitations: un-bounded Hilbert space

NON-UNITARY OPERATION FOR A REGISTER OF QUBITS



$$U^{\dagger}U = UU^{\dagger} = I$$

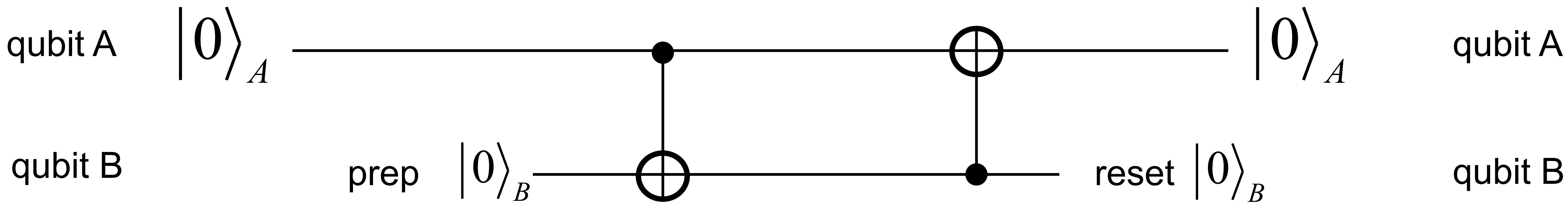
$$\langle \Psi | \Phi \rangle \rightarrow \langle \Psi' | \Phi' \rangle = \langle \Psi | \Phi \rangle$$



$$\sum_j K_j^{\dagger} K_j = I$$

$$\langle \Psi | K_j^{\dagger} K_j | \Psi \rangle = p_j$$

QUBIT STATE STABILIZATION VIA AUXILIARY QUBIT



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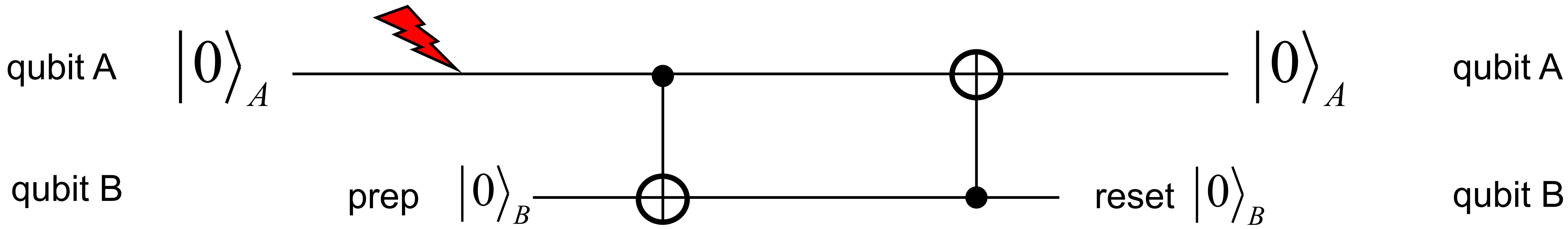
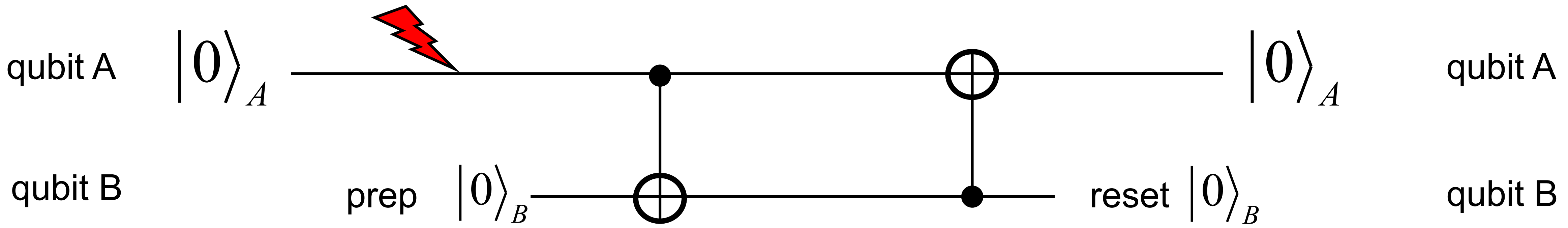


QUBIT STATE STABILIZATION VIA AUXILIARY QUBIT

$$\left(\lambda|0\rangle_A + \mu|1\rangle_A\right)|0\rangle_B \rightarrow \left(\lambda|0\rangle_A|0\rangle_B + \mu|1\rangle_A|1\rangle_B\right) \rightarrow |0\rangle_A\left(\lambda|0\rangle_B + \mu|1\rangle_B\right)$$



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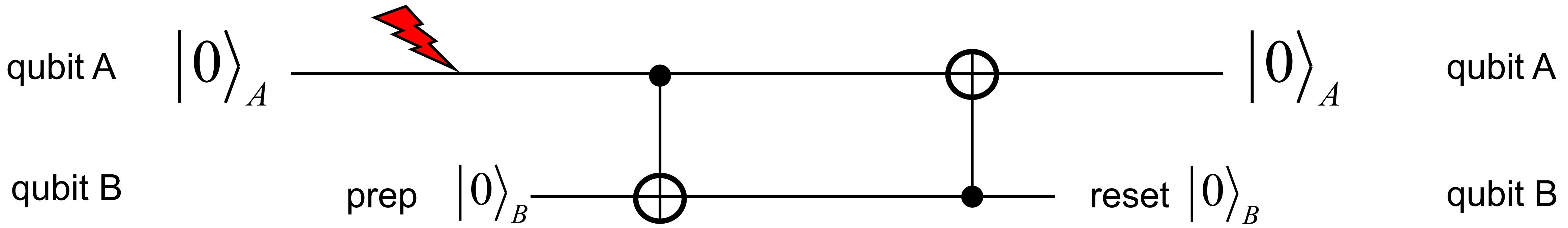

$$U = e^{\frac{i\pi}{2}\sigma_z^A \sigma_x^B} \qquad \tilde{U} = e^{\frac{i\pi}{2}\sigma_x^A \sigma_z^B}$$

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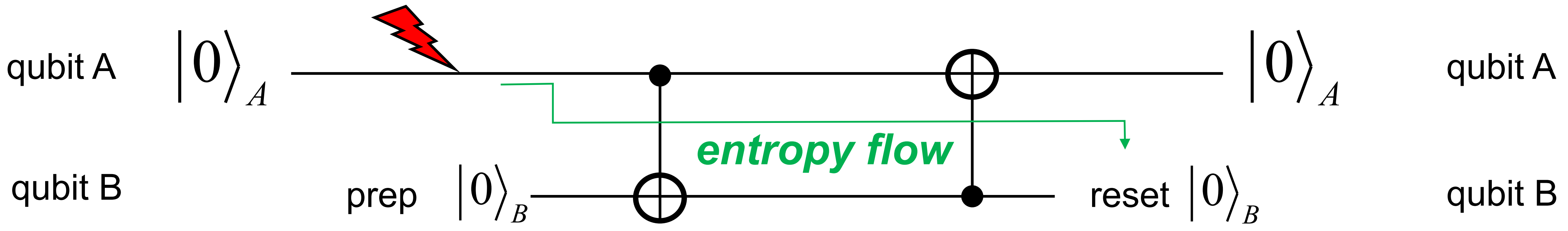

$$U = e^{\frac{i\pi}{2}\sigma_z^A \sigma_x^B} \qquad \tilde{U} = e^{\frac{i\pi}{2}\sigma_x^A \sigma_z^B}$$

IMPLEMENTATIONS OF QUBITS FOR QUANTUM INFORMATION

PHYSICAL SYSTEM	State of matter	Readout of single qubits	Control of operations	Quantum degree of freedom
Trapped ions Neutral atoms	Independent atoms in vacuum	Optical	Microwave and optical	Microscopic
Superconducting circuits	Solid state	Microwave	Microwave	MACROSCOPIC
Quantum dots	Solid state	DC & microwave	Microwave	Microscopic
Impurities in solid matrix	Solid state	Optical & microwave	Microwave and optical	Microscopic

A MACROSCOPIC DEGREE OF FREEDOM THAT IS QUANTUM?

Leggett, 1980

SIMPLEST EXAMPLE: **LC** OSCILLATOR CIRCUIT

T = 20mK

~ 1mm

MICROFABRICATION → L ~ 3nH, C ~ 1pF, $\omega_r/2\pi$ ~ 6GHz

CELL PHONE FREQUENCY, OPTIMAL ELECTRONICS CONTROL

A MACROSCOPIC DEGREE OF FREEDOM THAT IS QUANTUM?

SIMPLEST EXAMPLE: **LC** OSCILLATOR CIRCUIT

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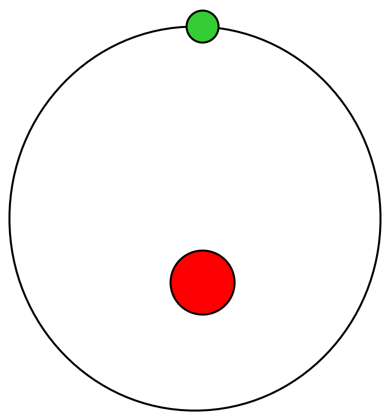
MICROFABRICATION → $L \sim 3nH$, $C \sim 1pF$, $\omega_r/2\pi \sim 6GHz$

CELL PHONE FREQUENCY, OPTIMAL ELECTRONICS CONTROL

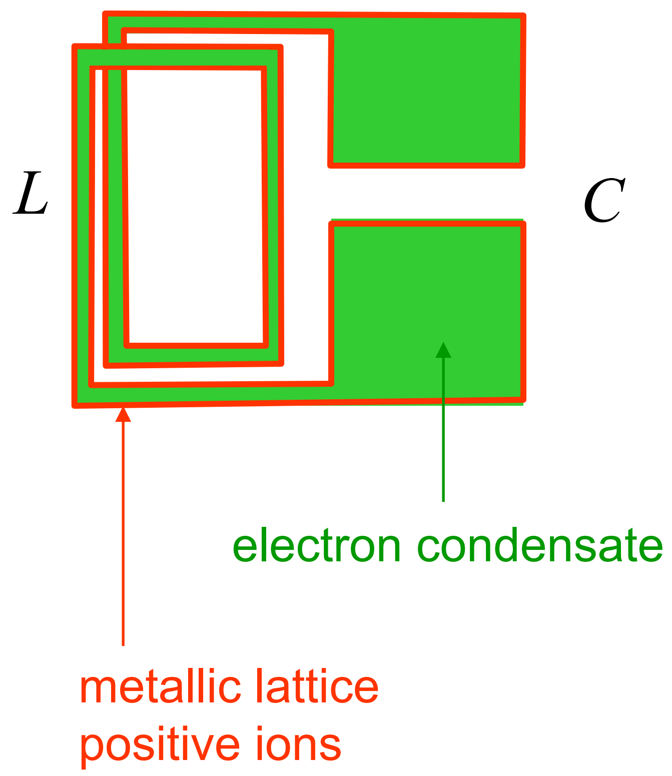
CHARGE ON PLATES SLOSHES BACK AND FORTH,
INTERNAL MODES ARE FROZEN.
ALL THE ELECTRONS BEHAVE AS A SINGLE CHARGE CARRIER

ATOM vs CIRCUIT

Hydrogen atom



Superconducting
LC oscillator



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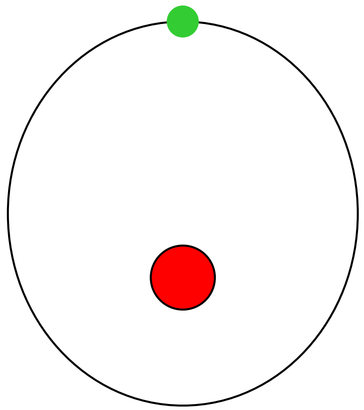

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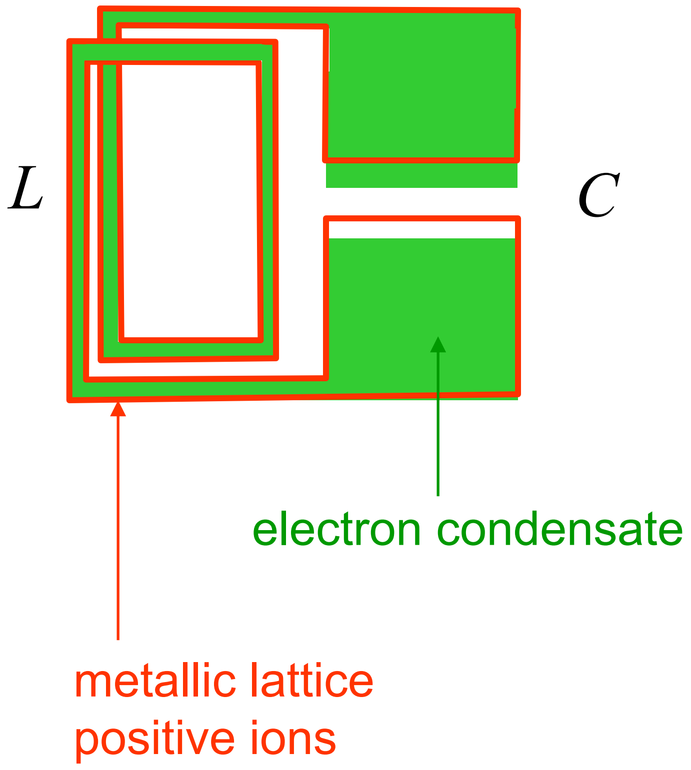

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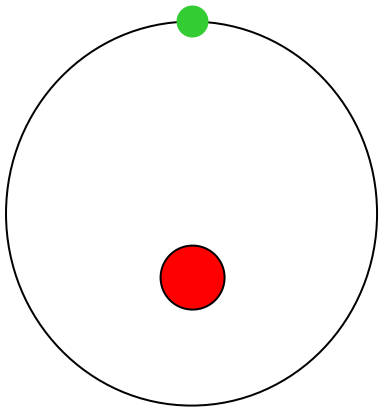

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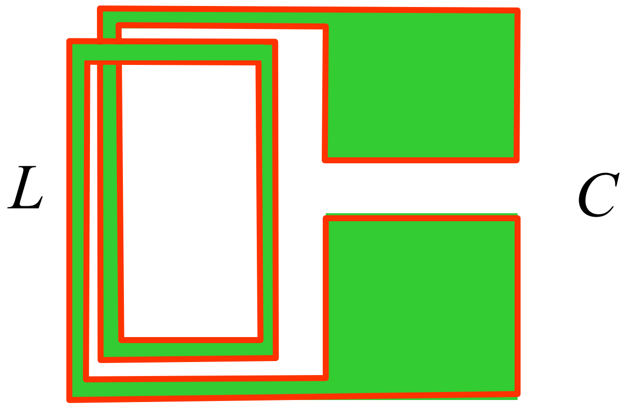
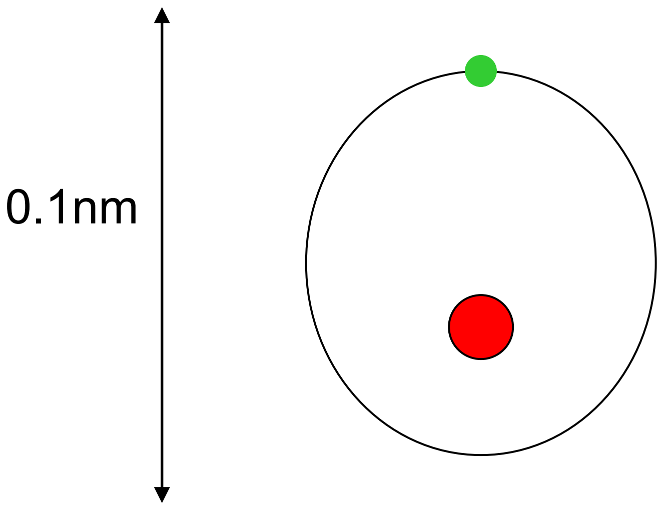


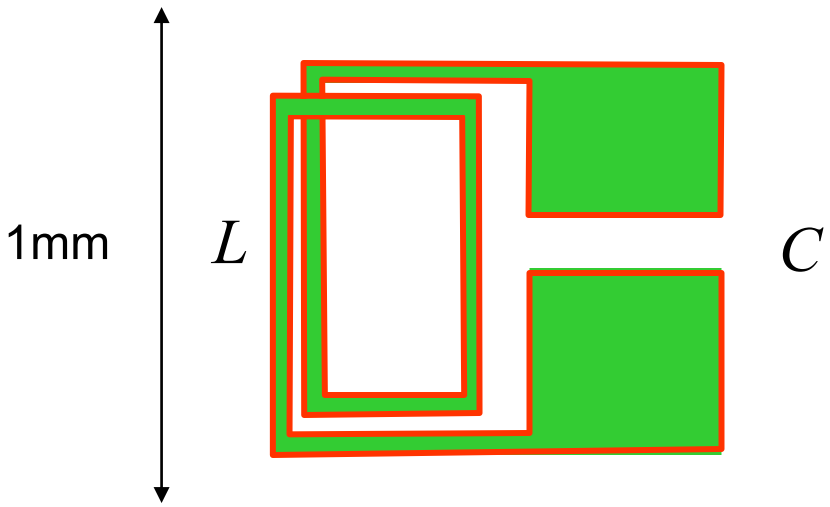
unique electron → whole superconducting condensate
velocity of electron → **current through inductor**
force on electron → **voltage across capacitor**

ATOM vs CIRCUIT

Hydrogen atom



Superconducting
LC oscillator



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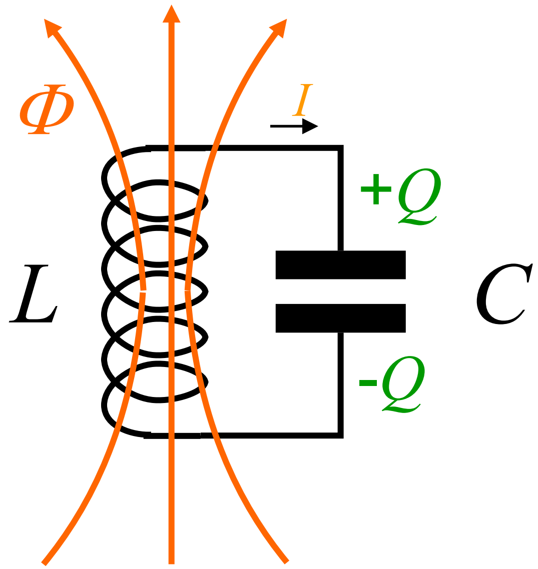
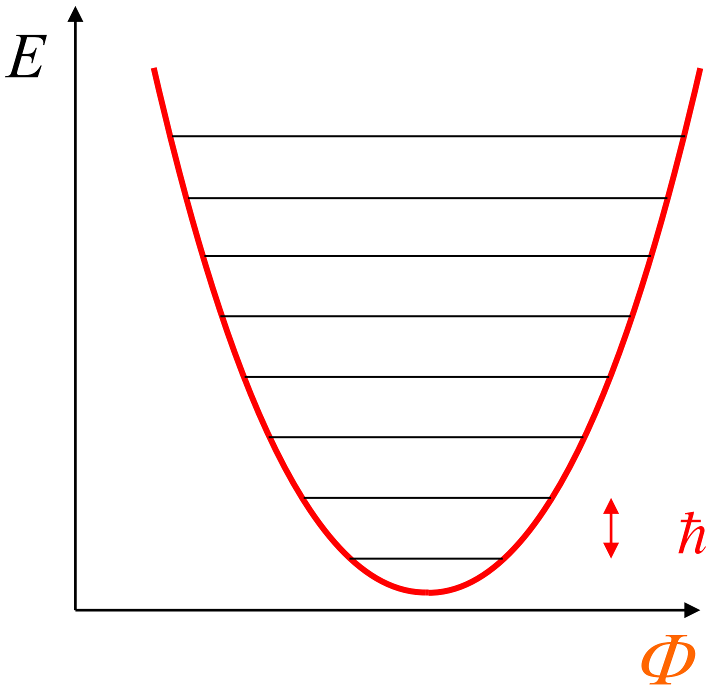
LC CIRCUIT AS A QUANTUM HARMONIC OSCILLATOR





$$\hbar\omega_{LC} = \frac{\hbar}{\sqrt{LC}}$$

$\Phi = LI$

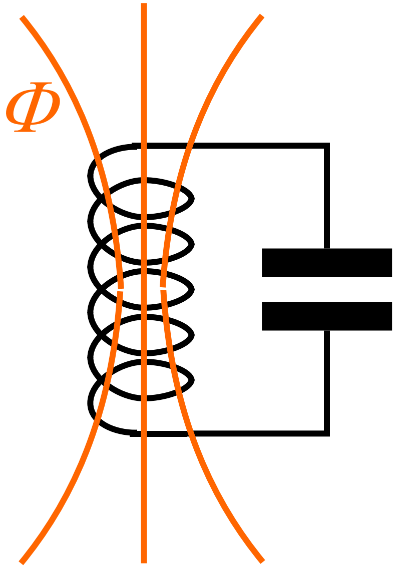
$Q = CV$

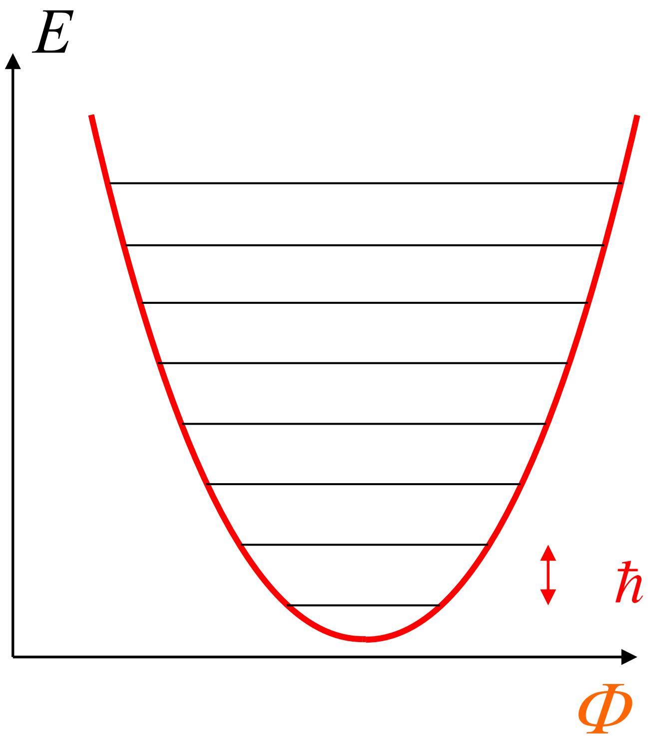
$$\left[\hat{\Phi}, \hat{Q}\right] = i\hbar$$

WAVEFUNCTIONS OF LC CIRCUIT

$$\frac{\hat{H}}{\hbar} = \omega_{LC}\left(\hat{a}^{\dagger}\hat{a} + \frac{1}{2}\right)$$

$$\hat{a} = \frac{1}{2}\left(\frac{\hat{\Phi}}{\Phi_{ZPF}} + i\frac{\hat{Q}}{Q_{ZPF}}\right)$$





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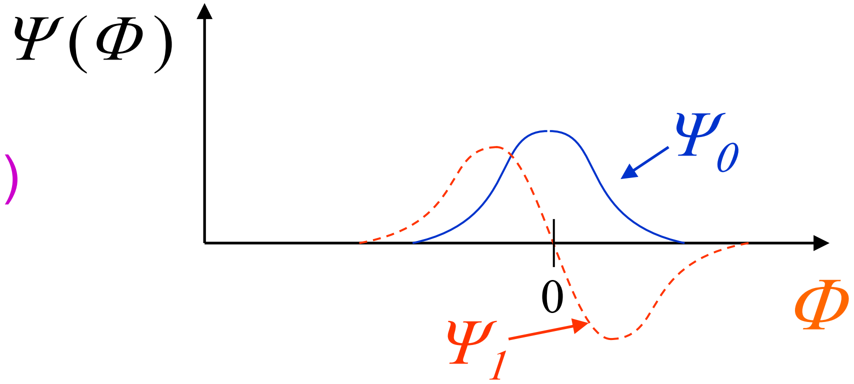
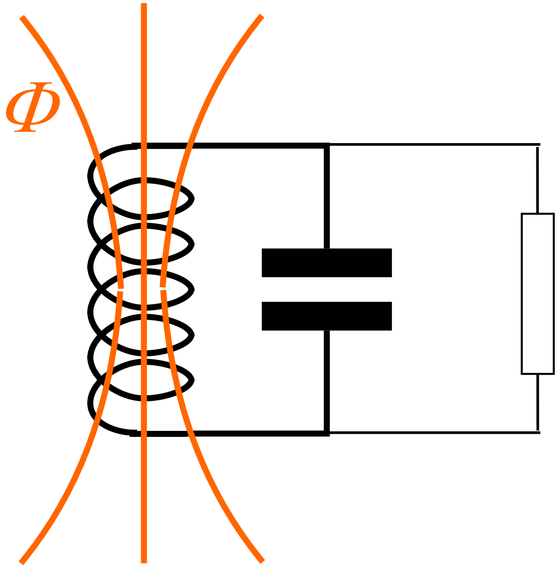
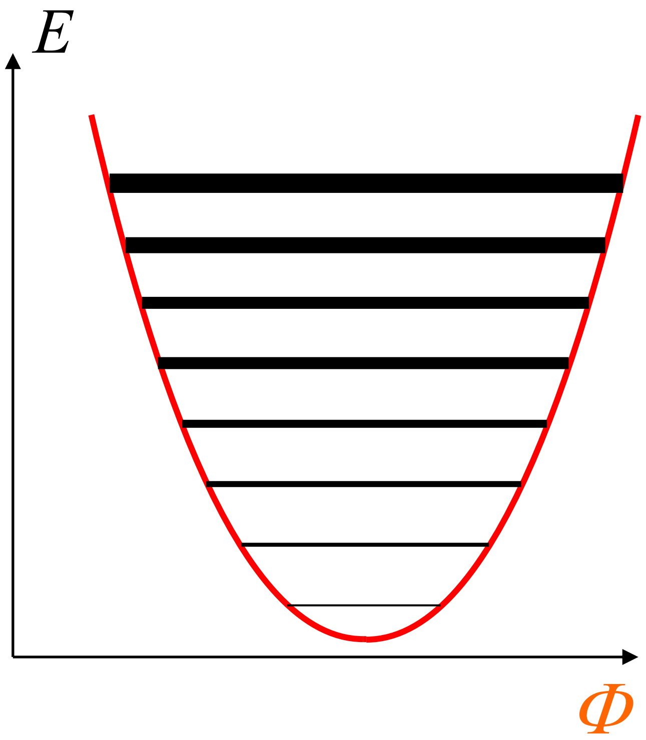


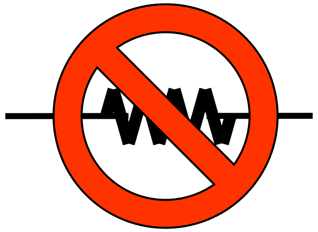
In every energy eigenstate,
(standing photon number state)
current flows in opposite
directions simultaneously!

EFFECT OF DAMPING





important: as little resistance as possible

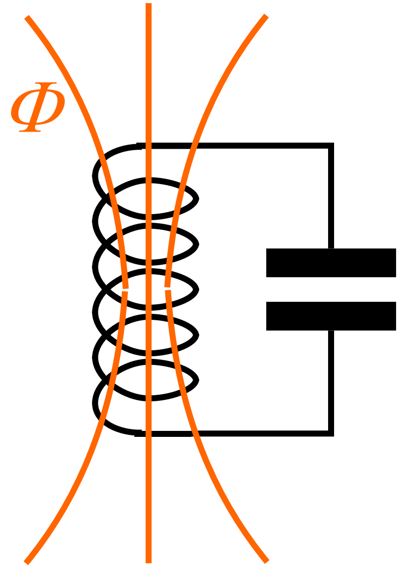


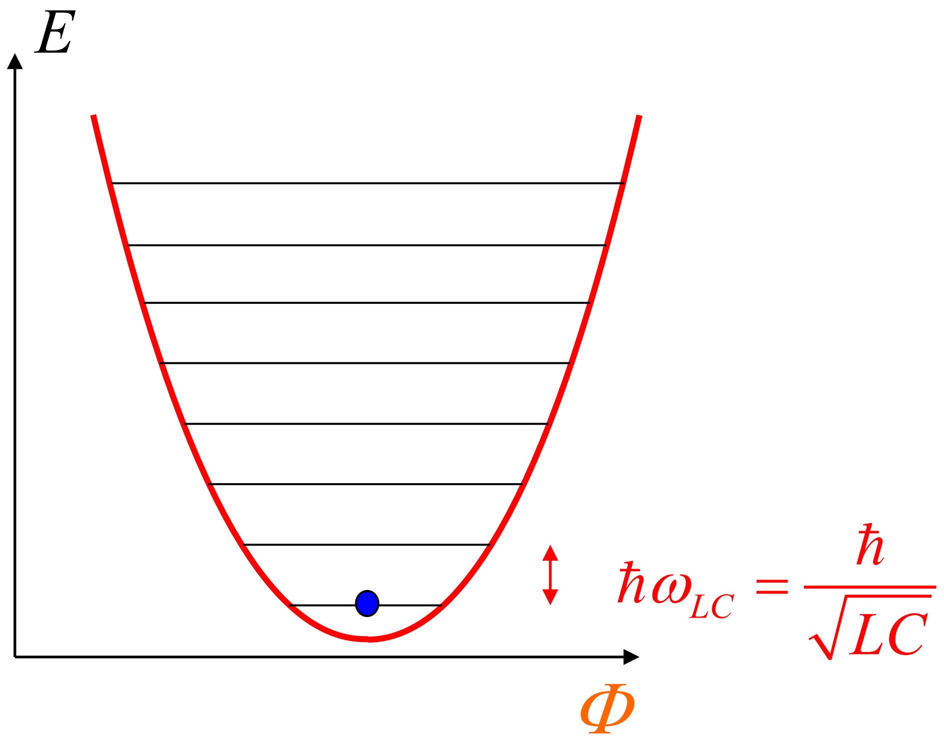
dissipation broadens energy levels

$$E_n = \hbar\omega_{LC}\left[n\left(1+\frac{i}{2\mathcal{Q}}\right)+\frac{1}{2}\right]$$

$$\mathcal{Q} = RC\omega_{LC}$$

RESET: PLACE CIRCUIT IN ITS GROUND STATE





some cold dissipation is actually needed: provides reset of circuit!

$$\hbar\omega_{LC} \gg k_B T$$

10-5 GHz

10mK