A Prospective Approach to Energy Saving (Reversible) Computing

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Highlights

- **Key theoretical discoveries in the area of Reversible Computing (RC) have been made in sixties and seventies by Landauer and Bennett. We closely followed their theoretical recommendations.**
- **Superconducting Josephson junction technology is the optimal choice for RC because allows to eliminate static energy losses.**
- **Any prospective computing technology must satisfy a long list of requirements. Earlier suggestions for RC superconducting gates satisfied only a few of them. Our recent solution based on nSQUID gates is quite close to the requirement list. As a result, we experimentally approached to the thermodynamic threshold.**
- **The most significant step was the elimination of multi-phase AC biasing schemes that are quite common for RC.**
- **The next important step could be a matching RC circuitry with a more conventional computing technology.**

Competition for a Lower Energy Dissipation

(It has been discovered long ago that logic reversibility and thermodynamics set limitations for energy dissipation)

Only erasure of the information costs energy [R. Landauer]. This conclusion leads to the concept of logically reversible computation which avoids erasure of the information [C. Bennett].

Our goal was to experimentally approach and even cross thermodynamic threshold for energy dissipation per logic operation: $k_B T \ln 2$ (~$4 \cdot 10^{-23}$ J at T=4.2 K)

R. Landauer, “Irreversibility and heat generation in the computing process,” *IBM J. of Res. and Devel.*, vol. 3, pp. 183-191, 1961.

C. Bennett, “Logical reversibility of computation”, *IBM J. of Res. and Devel.*, vol. 17, p. 525, 1973

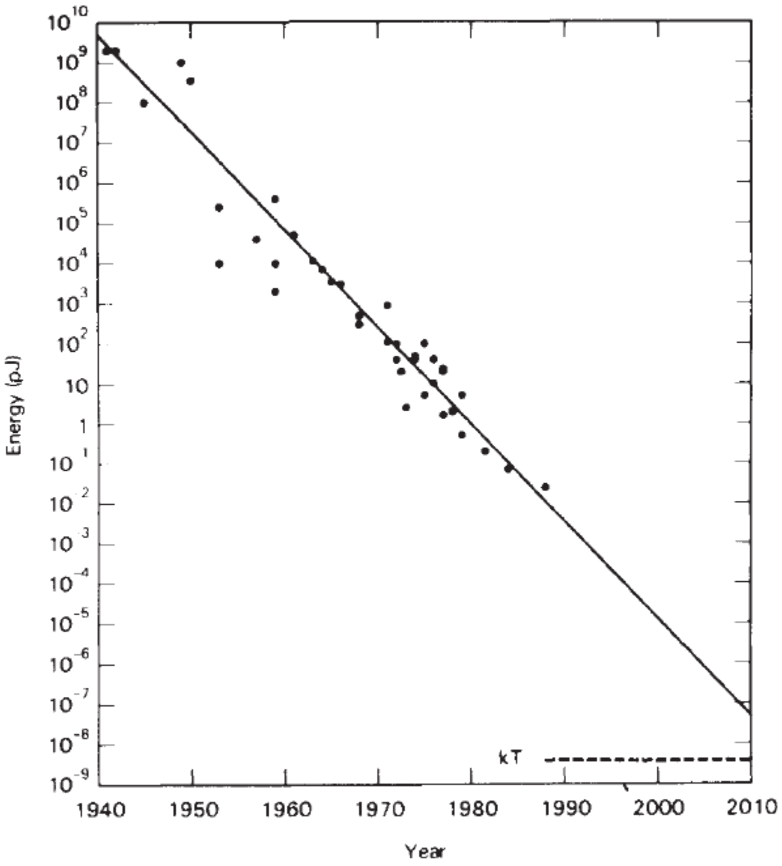
Impacts of Landauer Discoveries

The main paper
Title: Irreversibility and heat generation in the computing process
Author: **Landauer R**
Source: IBM JOURNAL OF RESEARCH AND DEVELOPMENT
Volume: 5 Issue: 3 Pages: 183-191 Published: 1961
Times Cited: **687**

With the so high number of citation it is possible to find papers of any kind, in particular those that give new proofs of Landauer principles and paper that explain why the principles are incorrect. However, about 2/3 of papers deal with reversible algorithms for Quantum Computing. This is because almost any Quantum Computers could be also named as a Reversible Computer operating in a quantum mode.

This is a quite strong observation because it immediately leads to a natural question: Why QC researchers bypass the more simple classical mode of operation? It is so usual to start any big project from execution simple tasks. Probably we are the only group that tried to design and experimentally demonstrate Classical Reversible Computing.

Unprecedented Accuracy of R. Landauer Forecast



The decrease in energy dissipated per logic operation over recent decades.

In 1982 Landauer collected available data that are reasonably fitted by a simple exponential approximation. The fitting line hits kT threshold in 2014. We are still in time to meet this forecast.

Another Good Illustration For Reversible Computing

(Landauer 1991)

Must information be discarded in computation, communication and the measurement process? This question has physical importance because discarding a bit of information requires energy dissipation of order *kT*.

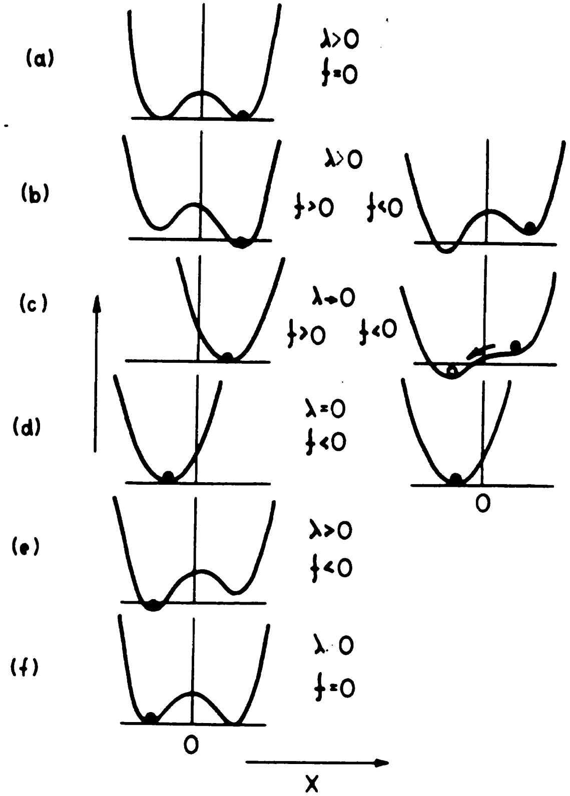
SIDNEY HARRIS

First Potentially Reversible Superconducting Circuits

-No energy dissipation in superconducting state;

-Very convenient and accurate energy potential: $E(\varphi)=I_C\,(\varphi_{cl})\cdot\Phi_0\cdot\cos(\varphi)$;

-Developed technology: CAD tools, fabrication, measurement.

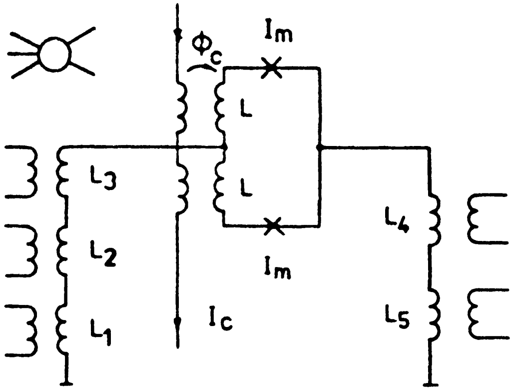


K.K. Likharev, “Classical and quantum limitations on energy consumption in computation,” *Int. J. Theor. Phys.*, vol. 21, p. 311, 1982.

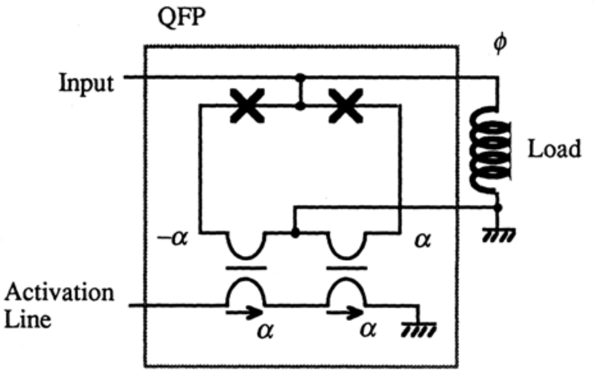
Parametric Quantron

also Known as Quantum Flux Parametron, Double SQUID, IN-SQUID, Flux and Ground-state Qubit

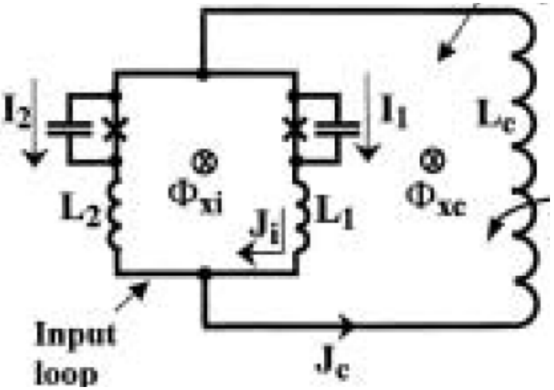
"Parametric Quantron", K.K. Likharev, and others 1985.



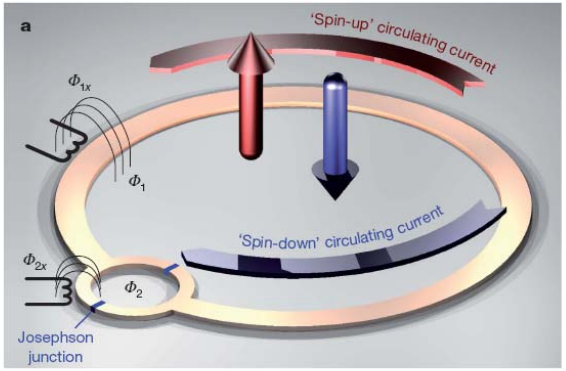
"DC or Quantum Flux Parametron", E.Goto and others, 1986



"IN-SQUID", J. Clarke and others, 2002

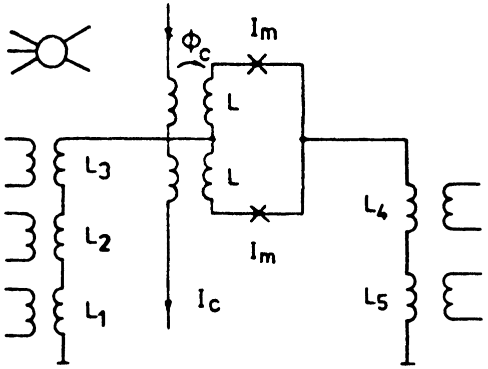


"Ground State Qubit", M. W. Johnson, and others, 2011.

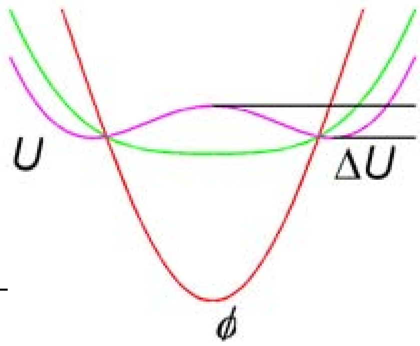


We mentioned only most common names given to almost identical devices that could be described as a superconducting inductance shortened by an externally controlled two-junction SQUID.

Properties of Inductance Shortened by Externally Controlled Two-Junction SQUID

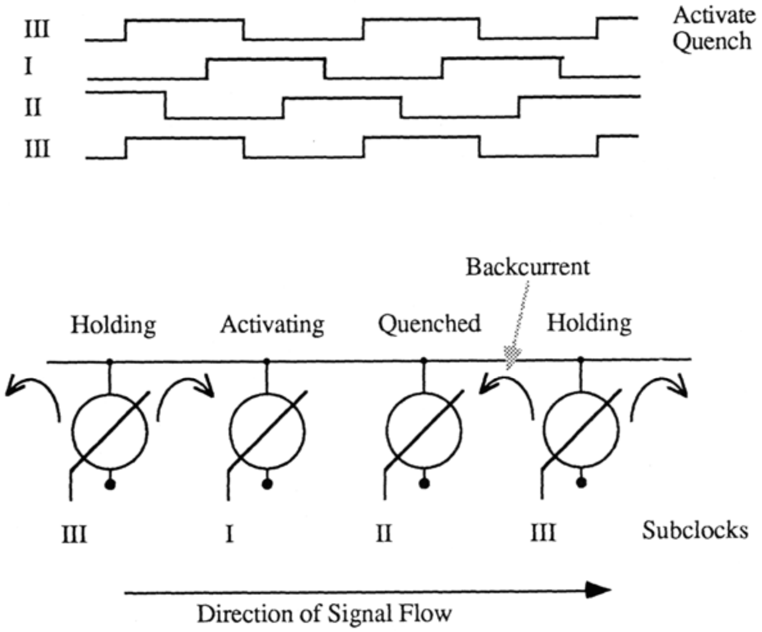


$$\frac{U(\varphi,\varphi_+)}{\Phi_0 I_m/2\pi} = \left(\frac{(\varphi_+-\varphi_c)^2}{l}+\frac{(\varphi-\varphi_e)^2}{\Sigma l_i}\right)-2\cos\varphi\cos\varphi_+$$

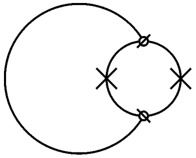


The effective critical current and therefore the energy profile of the device is controlled by external current. This (AC) current delivers and takes energy to and from the cell. In other words, it serves as a bias current. At the same time it serves as a clock signal. In general, this is not good because several clock signal could be required to control complex logic circuits.

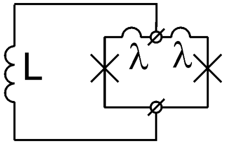
As a example, the circuits developed in Goto group use 3-phase clocking scheme.



Double SQUID Easily Metamorphoses into nSQUID



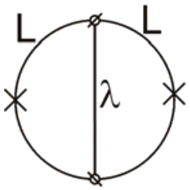
(a)



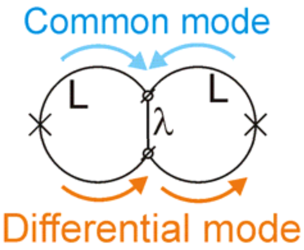
(b)

$$\frac{U(\varphi_-,\varphi_+)}{\Phi_0 I_C/2\pi}=\left(\frac{(\varphi_+-\varphi_c)^2}{(L+\lambda/2)/2}+\frac{(\varphi_--\varphi_e)^2}{\lambda}\right)-2\cos\varphi\cos\varphi_+$$

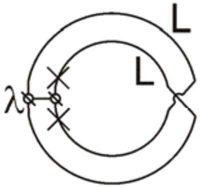
In particular, they are described by similar equations. Advantages of one or another geometry partly depend on personal preferences.



(c)



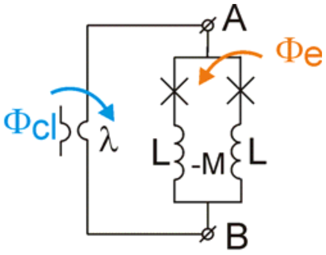
(d)



(e)

This is because until now we assume that the compared devices are weakly coupled with other devices. In plain words, standalone double and nSQUIDs are quite similar.

Everything is changed if we think about much larger systems built of strongly coupled SQUIDs.

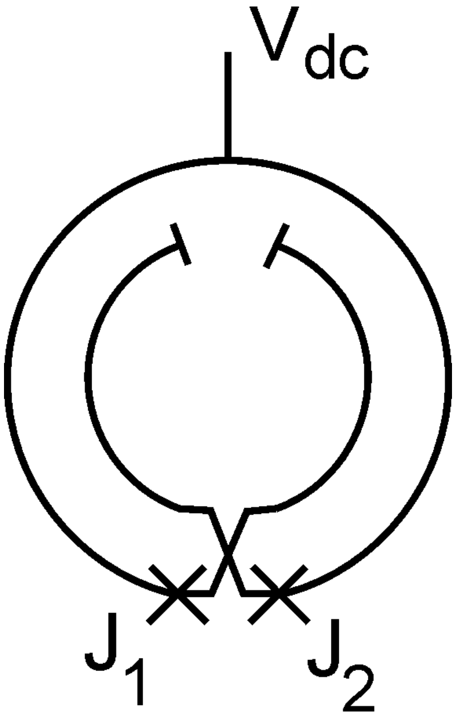


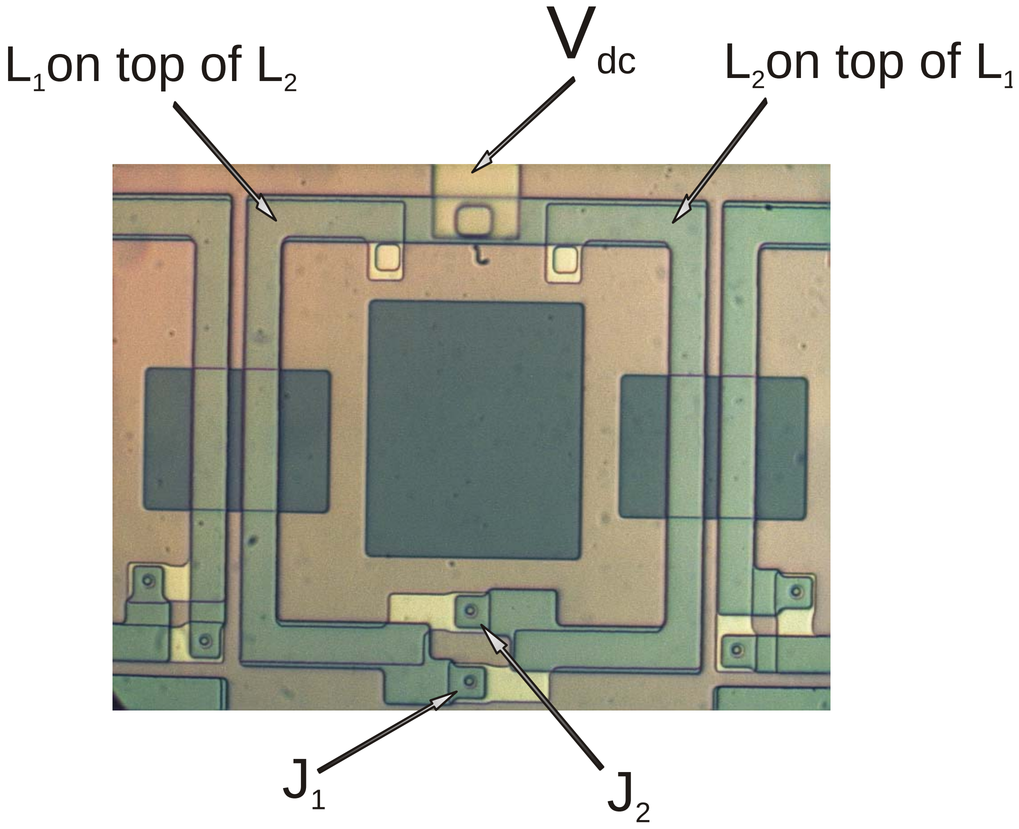
(f)

$$\frac{U(\varphi,\varphi_+)}{\Phi_0 I_C/2\pi}=\left(\frac{(\varphi_+-\varphi_c)^2}{\lambda/2+(L-M)}+\frac{(\varphi_--\varphi_e)^2}{(L+M)}\right)-2\cos\varphi_-\cos\varphi_+$$

$\varphi\pm=(\varphi1\pm\varphi2)/2$

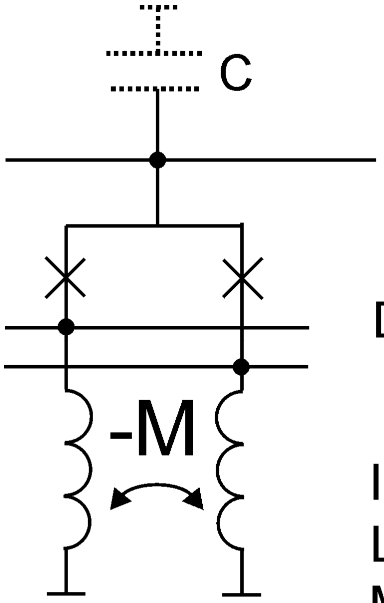
The First nSQUID Layout (ASC 2002)





The circuit fabricated at HYPRES, Inc. Target Ic = 0.015 mA. Dark areas are the ground plane holes. The left and right holes are used for magnetic coupling with other nSQUIDs

Schematics and Layouts of nSQUIDs (type c) with Galvanic Coupling



nSQUID

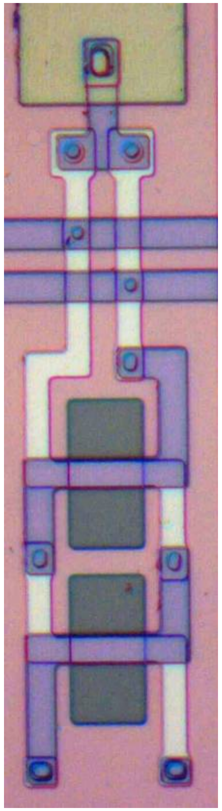
Clock line

Differential data lines

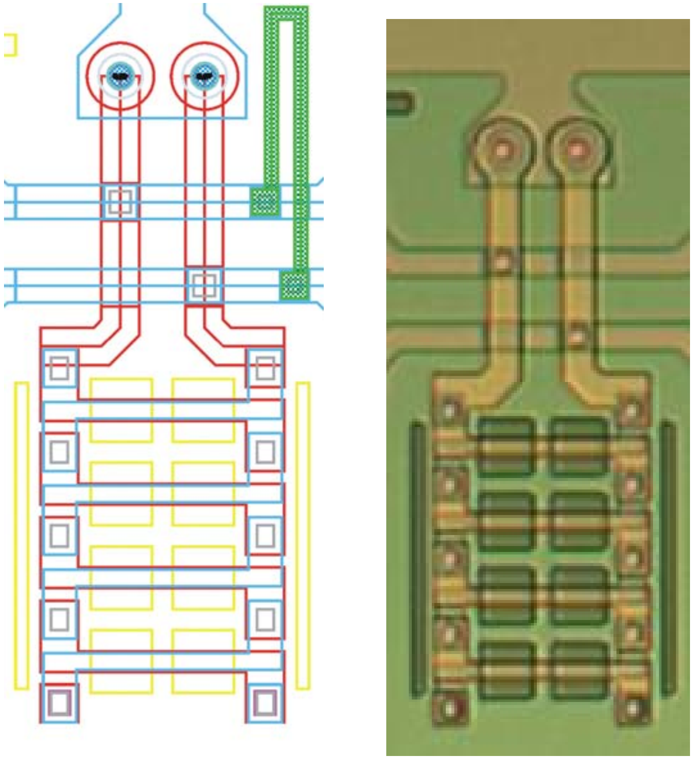
Ic= 0.01 mA

L=26 pH

M=-20 pH

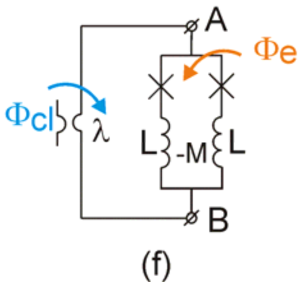


Year 2004

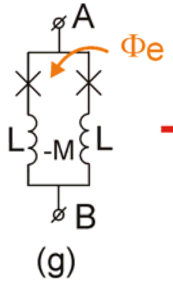


Year 2007-08

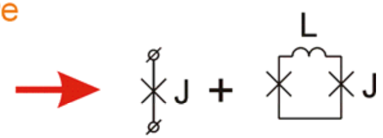
nSQUIDs as Building Blocks for Large Circuits

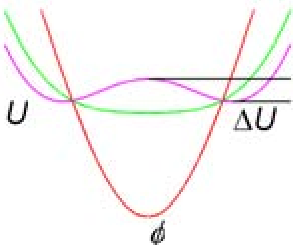


(f)

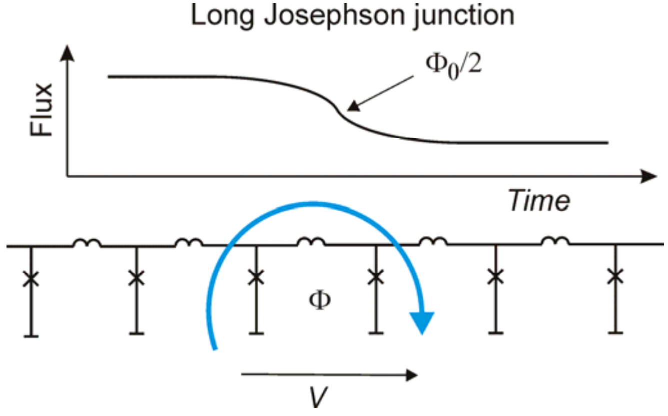


(g)

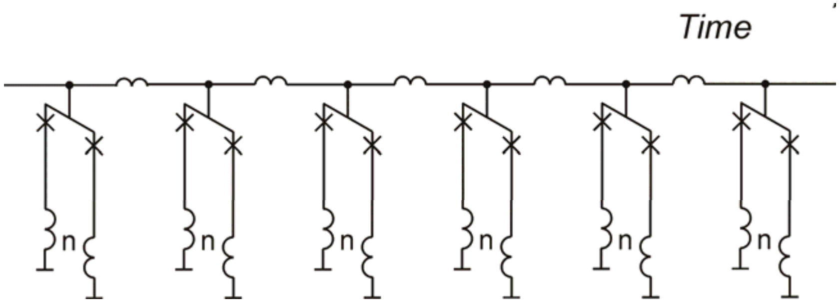




JJ phase drop controls (or clocks) the SQUID energy profile from mono-stable at $\phi_{cl}=0$ to bi-stable at $\phi_{cl}=\pi$

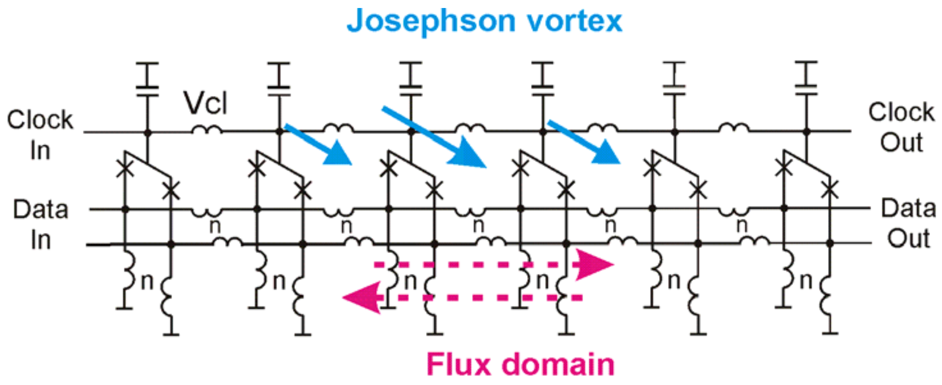


Fluxons or Josephson vortices can freely move along long Josephson junctions with arbitrary speed *V* that depends only on initial and boundary conditions. (Properties of long JJs are discussed by A. Ustinov.)



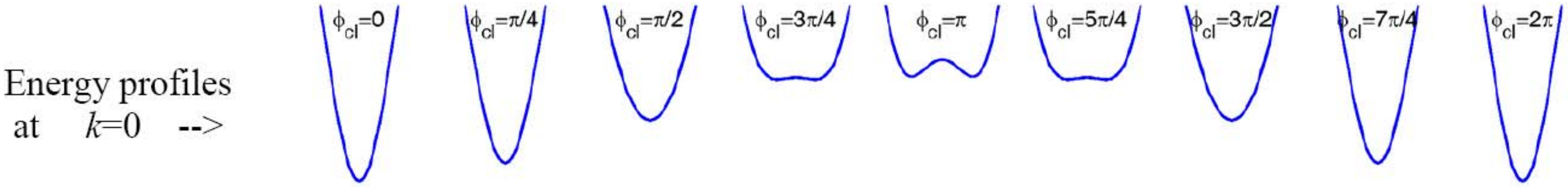
A long Josephson junction could be made of nSQUIDs. The SQUIDs located near the center of a moving or resting vortex have bistable energy profile and they should randomly "fall" into one of two energy minimums.

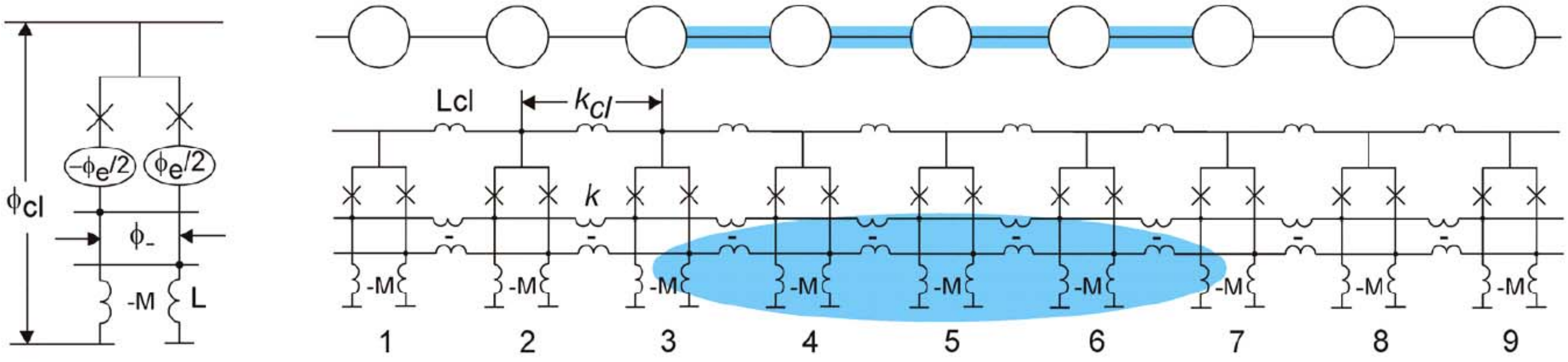
String of nSQUID is one of the Simplest Digital Circuits



Let us magnetically couple of neighbor nSQUIDs. Such mutual biasing should force all nSQUIDs belonging to one Josephson vortex to select the same energy minimum.

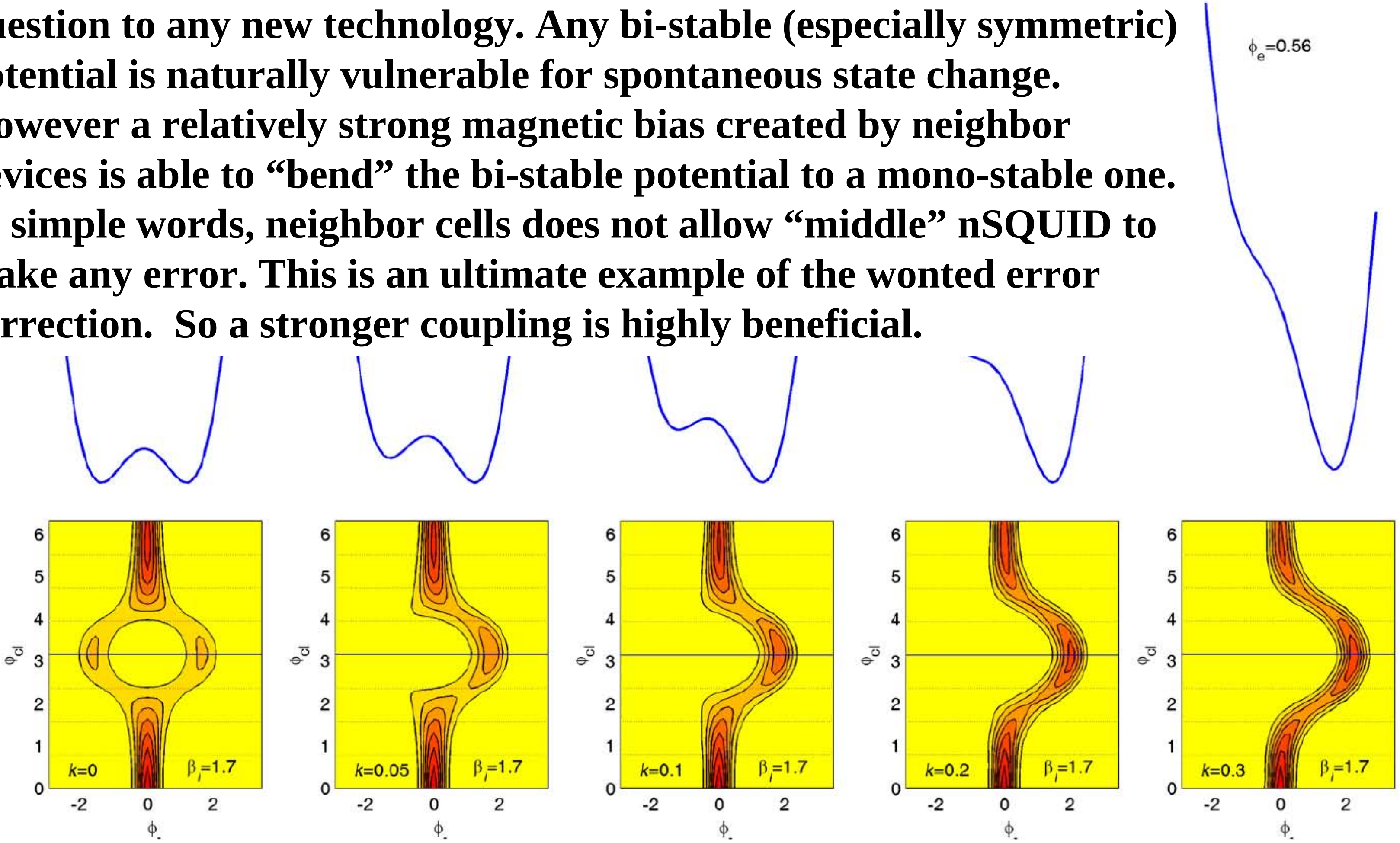
Sketches below show energy profiles when one vortex occupies 8 nSQUIDs and the coupling is vanishingly low.





nSQUID Energy Profiles at Different (increasing) Couplings

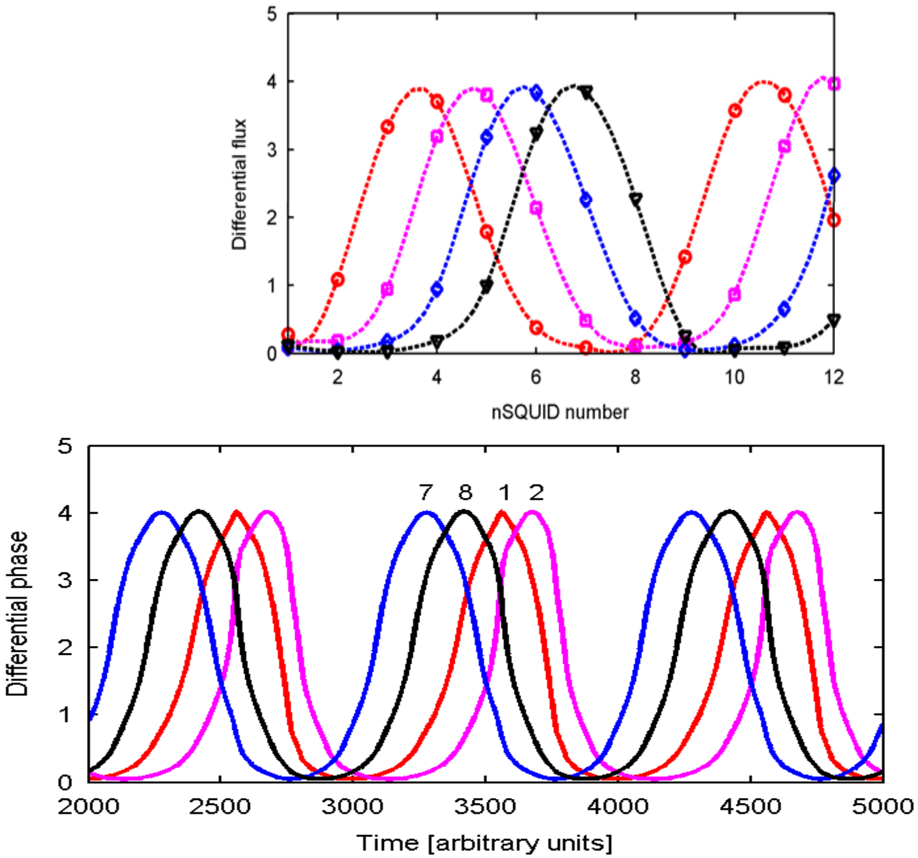
Error rates and error correction are among the first technical question to any new technology. Any bi-stable (especially symmetric) potential is naturally vulnerable for spontaneous state change. However a relatively strong magnetic bias created by neighbor devices is able to "bend" the bi-stable potential to a mono-stable one. In simple words, neighbor cells does not allow "middle" nSQUID to make any error. This is an ultimate example of the wonted error correction. So a stronger coupling is highly beneficial.



The only lost group of people are theoreticians. This is because there is no chance to analytically analyze any circuits built of many strongly coupled nSQUIDs. Fortunately numerical simulation are able to close this technical problem.

Dynamics of a Linear nSQUD Array
(numerical simulations)

There is a strong overlapping of bi-stable states of adjacent cells. At the selected 8-phase timing all cells are organized into bi-stable domains consisting of 3 to 4 cells and isolated by 5 to 4 mono-stable cells.



Pictures illustrate the evolution of differential phase with time. The upper plot shows that domains occupy about 4 cells and move along the array with a constant speed (strictly proportional to the applied DC voltage). The lower plot shows evolutions of differential phases in 4 different nSQUIDs.

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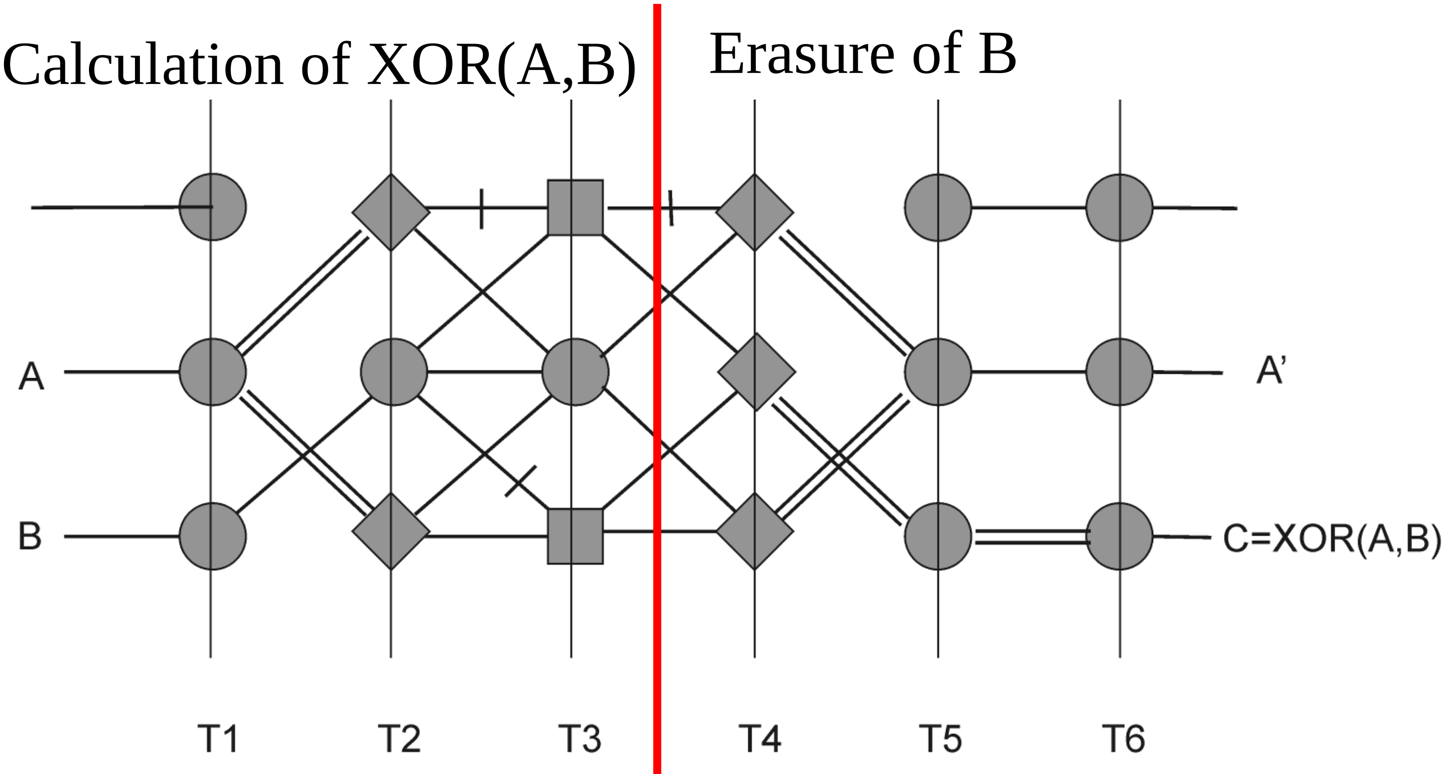
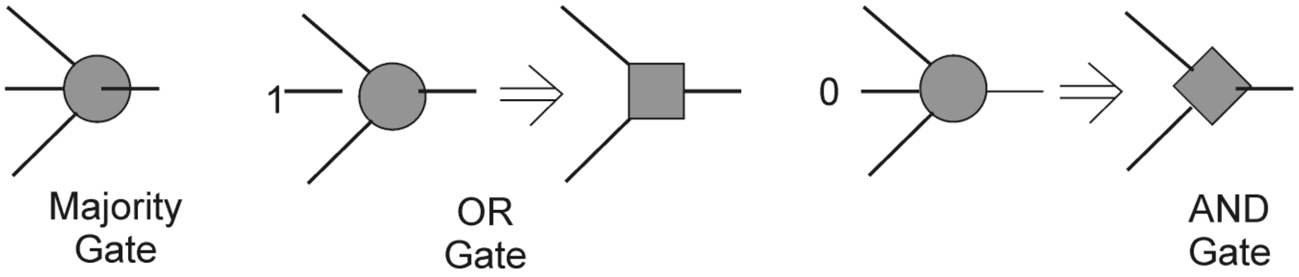
Application of Bennett's Technique to Design of XOR Gate

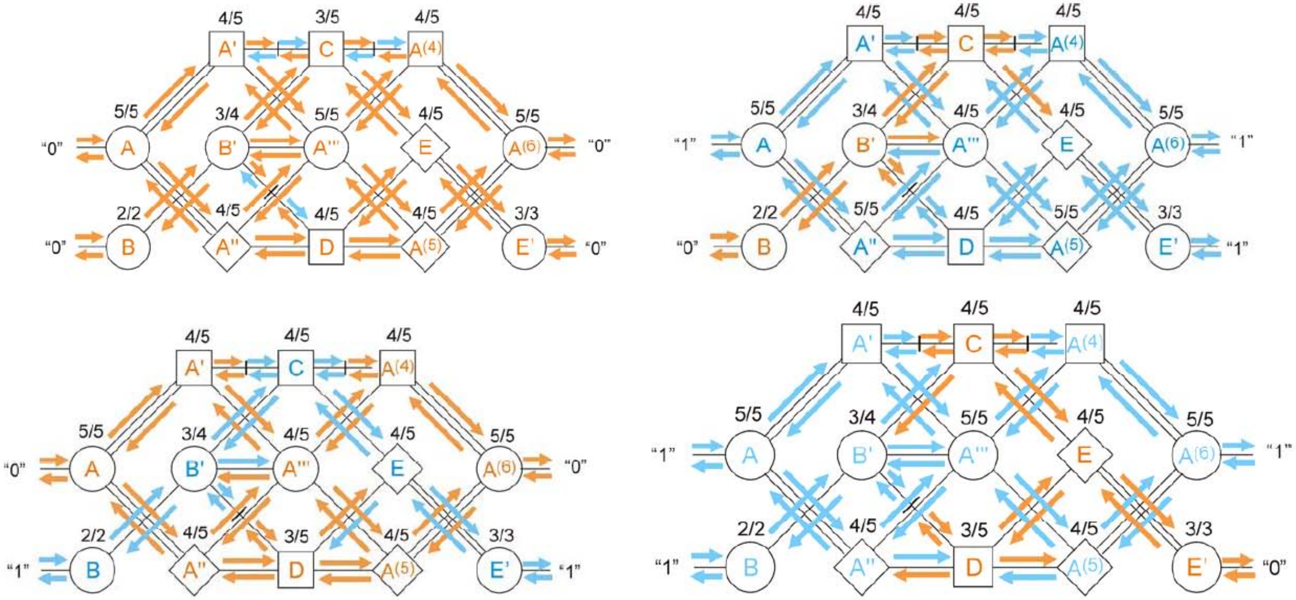


Calculation of XOR(A,B)

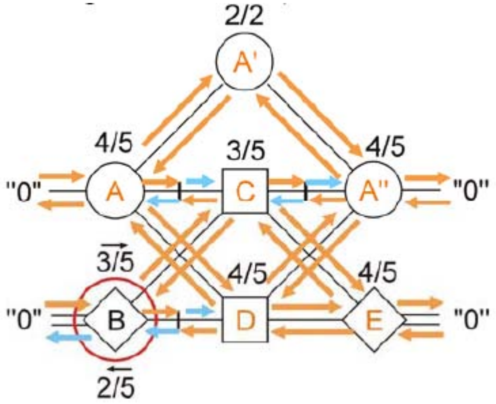
Erasure of B



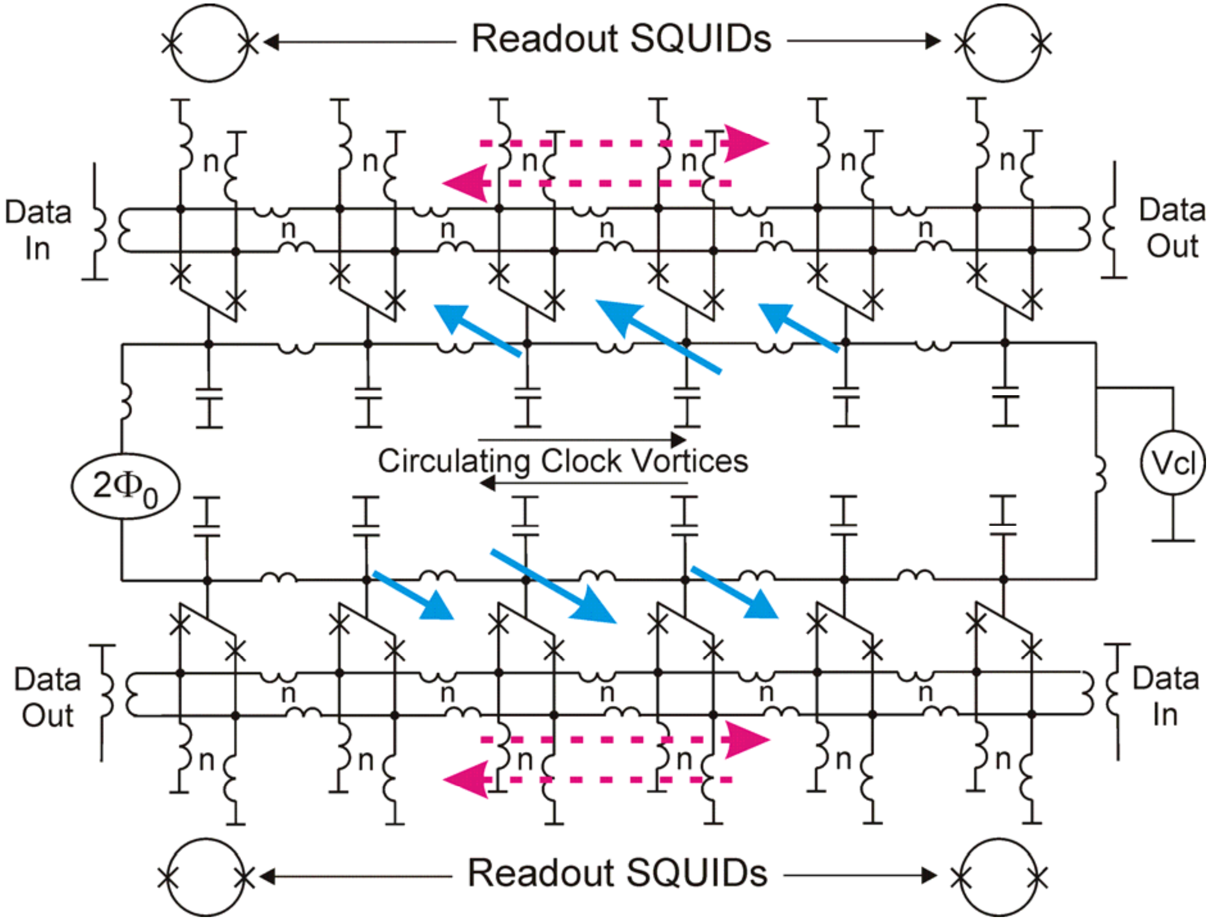
Comparison of Reversible and Irreversible nSQUID Circuits



Reversible XOR circuit (above) is larger than its irreversible counterpart (on the right). Each of four sketches corresponds different sets of input data. However, the reversible solution will be correct even at fluctuating direction of data propagation. Orange and blur arrows show propagation of logic “ones” and “zeros”. Both gates are suggested of Sergey Rylov master and PhD project. (Currently S. Rylov is with IBM Yorktown Heights.)



What Could be Made of Simple nSQUID Strings?



The shown circuit is two shift registers that share the common clock line. Two vortices are injected into the clock line. Vortices circulate along the line with the speed that completely defined by an external voltage source. The circuit has been fabricated at HYPRES, Inc. Direct measurements showed the specific energy dissipation about $3k_BT$ per 8 nSQUID shift register!

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Measurements of Energy Dissipation

Due to DC biasing it is possible to reduce energy measurements to much more simple current measurements

$$E_{th} = k_B T \ln 2$$

$$E = V \cdot I \cdot Period$$

$$I_{th} = (\ln 2 / \Phi_0) \cdot k_B Temp$$

$$1 / Period = (1 / \Phi_0) \cdot V$$

At $Temp$=4.2 K I_{th}=0.02μA

$$E = \Phi_0 \cdot I$$

Jie Ren will give more details about design and measurement procedures.

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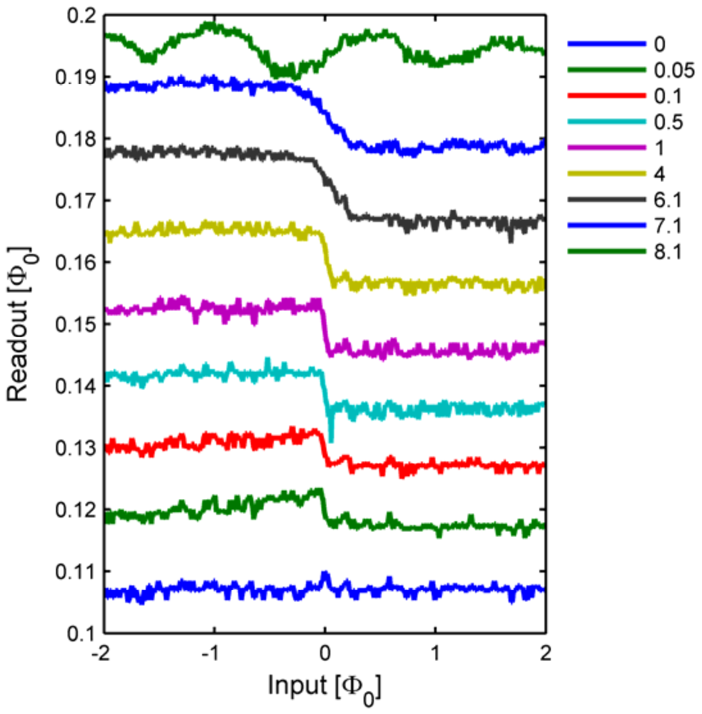
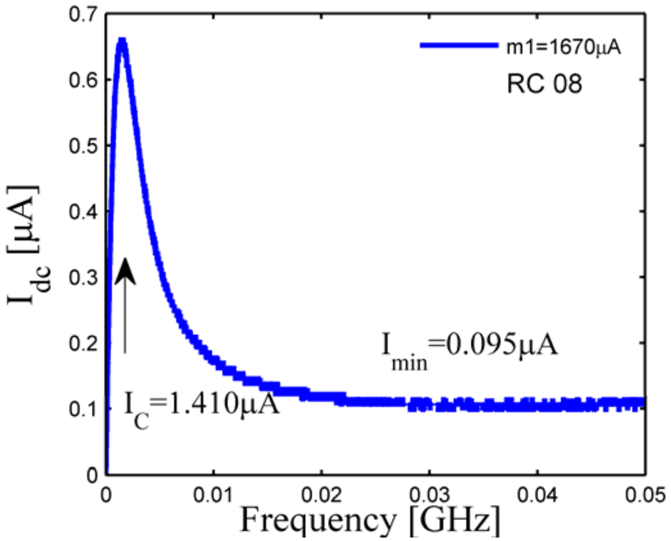
Measurement of the Energy Dissipation

Digitization of analog input magnetic flux and transfer it on about 2 mm distance, where the digitized signal is measured by a dc SQUID.

Legends show clock frequencies in GHz.



2 vortices in the clock loop. Frequency range 0.05 GHz to 7.1 GHz



Measurement of the energy dissipation (in fact, dc current flowing via the circuit.): Minimal current is around 2 times of the thermodynamic threshold value(0.04 μA).

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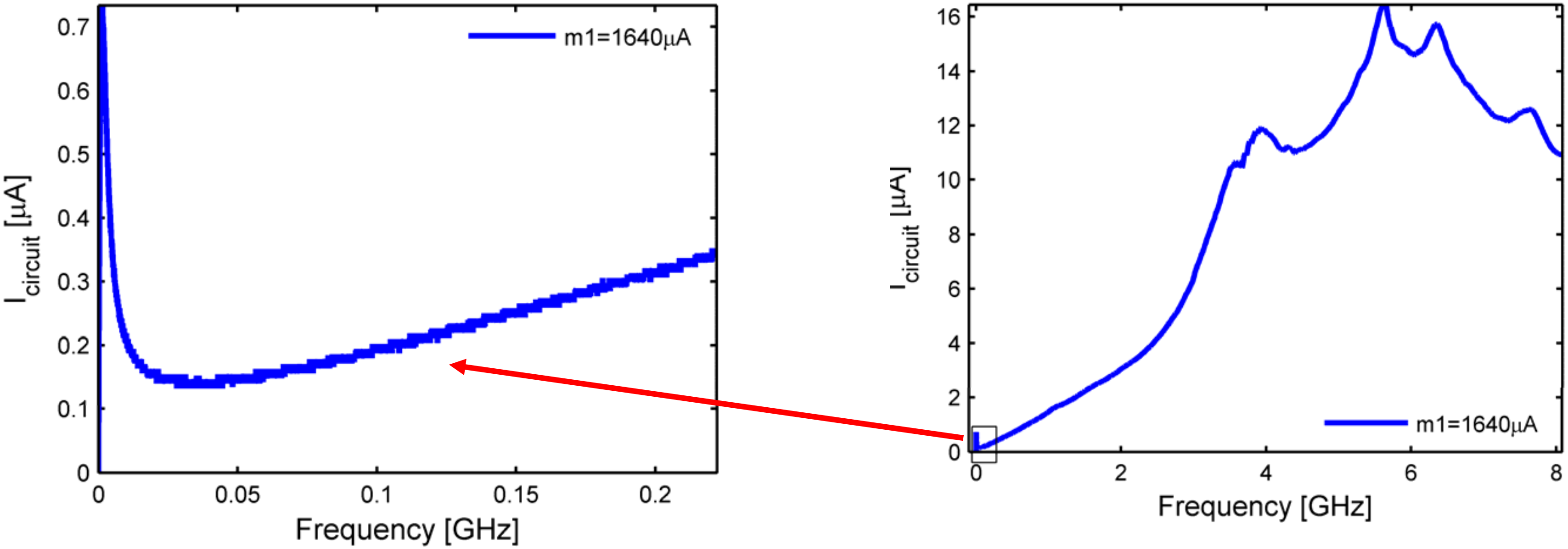
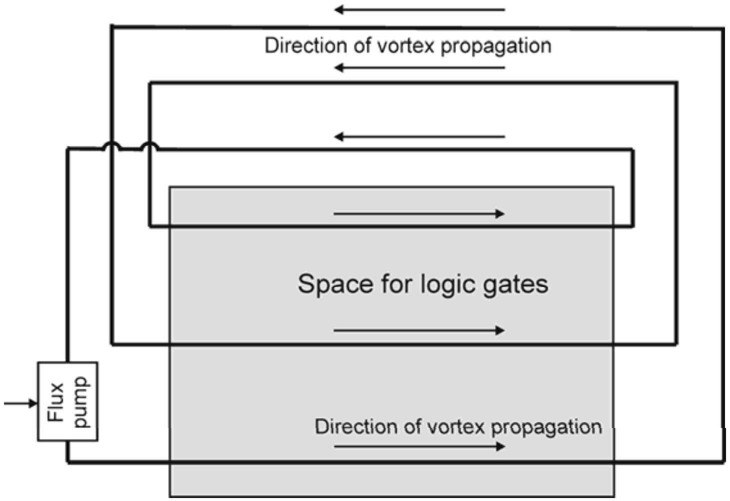
Measurement of Bias Current II.

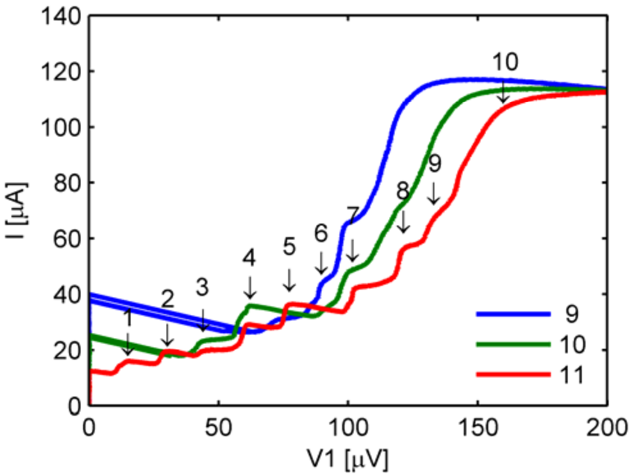


Architecture and System Issues: Timing Belt Clock Scheme



Two functionally similar “timing belts”. One is composed of long Josephson junctions and nSQUID strings. (both are shown as a black line) filled with vortices, while the other is a usual rubber belt used in cars.

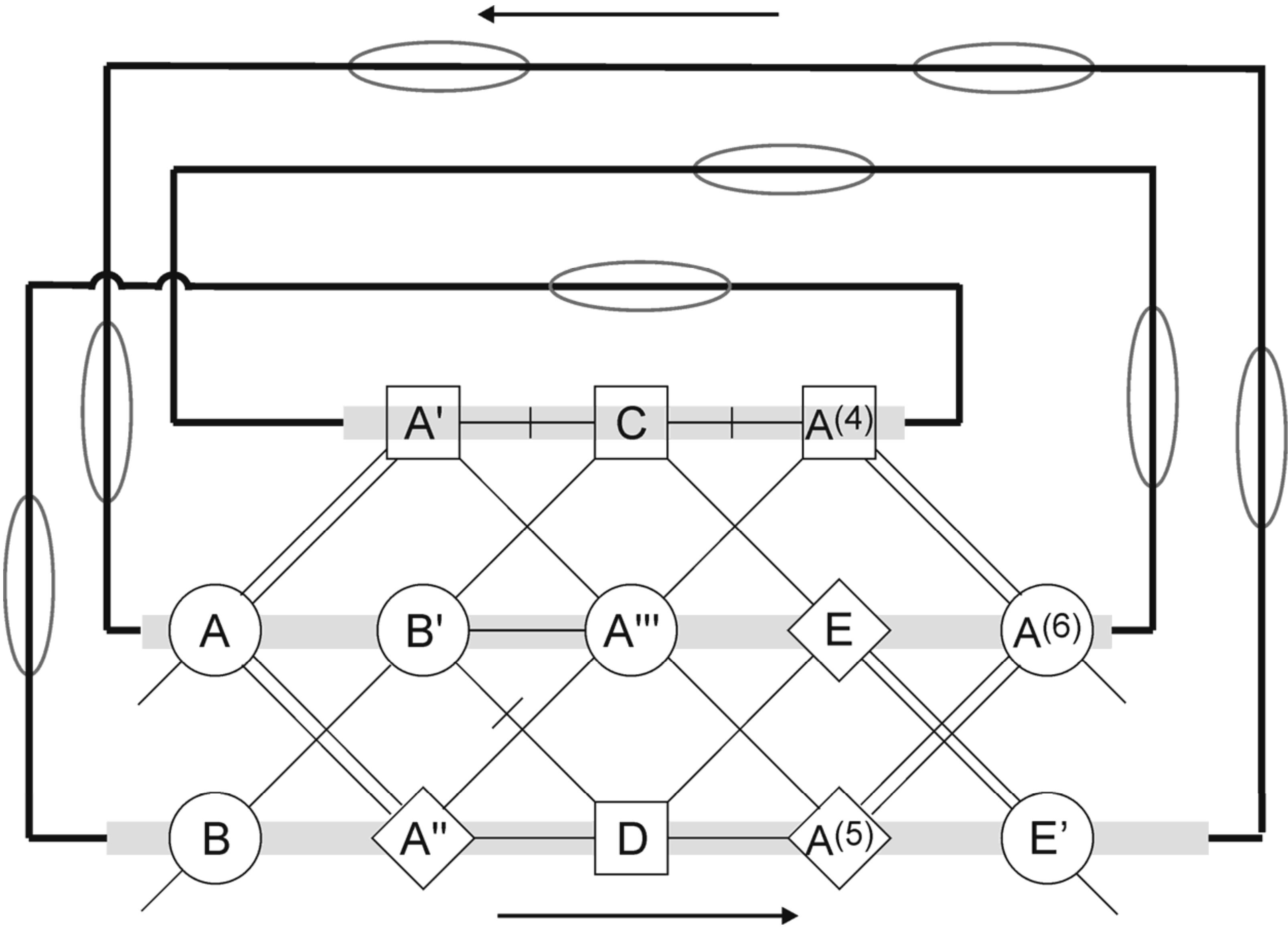
Experimental Investigation of Time Belt
Made of One Long Josephson Junction with 77 Junctions



Shown IV curves correspond to 3 different numbers of vortices in the belt. At 11 injected vertices one vortex occupies 7 junctions; at 10 and 9 injected vertices one vortex occupies accordingly about 7.7 and 8.6 junctions.

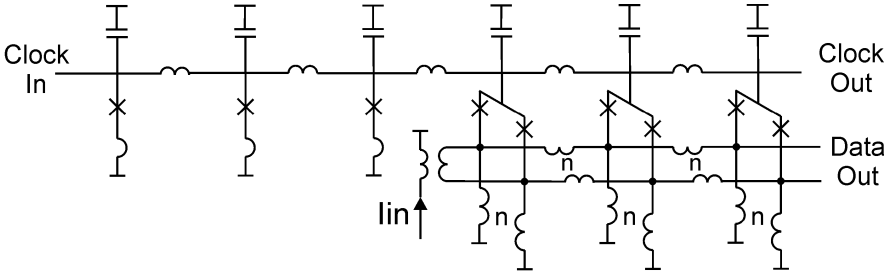
In nSQUID strings the vortices serve as multi-phase clocking devices. All vortices are identical and we may hope that they will be able to provide ideally accurate timing sequences. Moreover, simple numerical analysis showed that circuits with fractional (not integer) number of junctions or nSQUIDs per vortex dissipate dramatically lower power. It would be impossible to implement such sophisticated explicit clocking schemes. Ultimate simplicity and accuracy of the timing belt solution is probably the most fundamental advantage of our approach.
Closed long Josephson junction is a well investigated device but it was important for us to check that we are not affected neither design nor fabrication errors. A. Ustinov provided us educational support, while J. Ren designed and measured the circuit.

Timing Belt Serving Reversible XOR Gate Composed of Majority, OR and AND gates

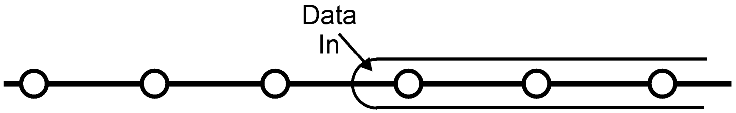


Important nSQUID Primitives

longJJ nSQUID Interface

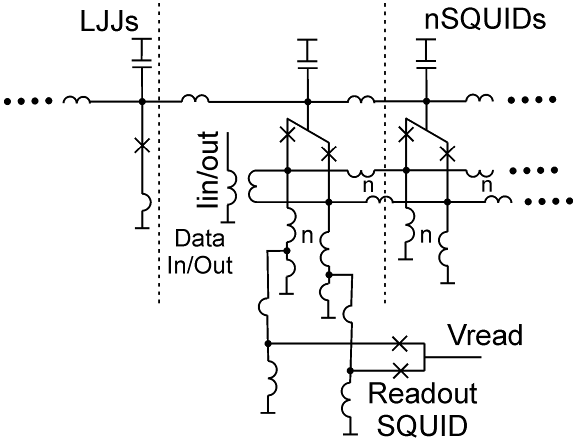


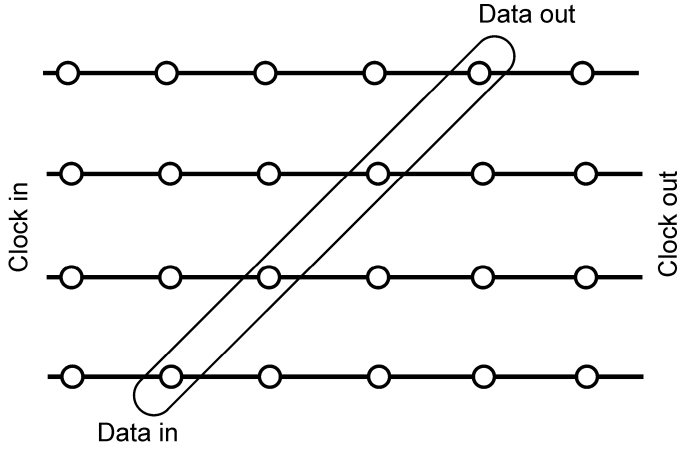
(a)



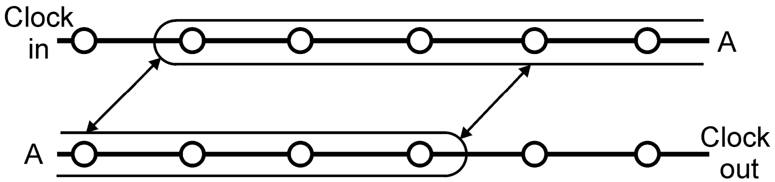
(b)

Optional SQUID readout



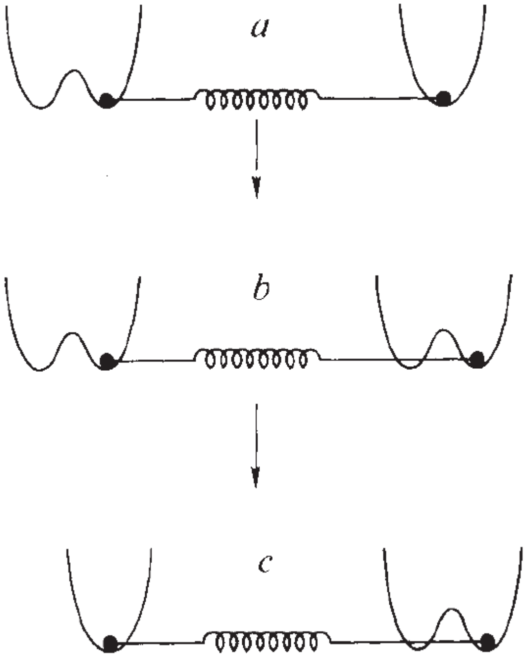


Copying and reversible Erasure of Data



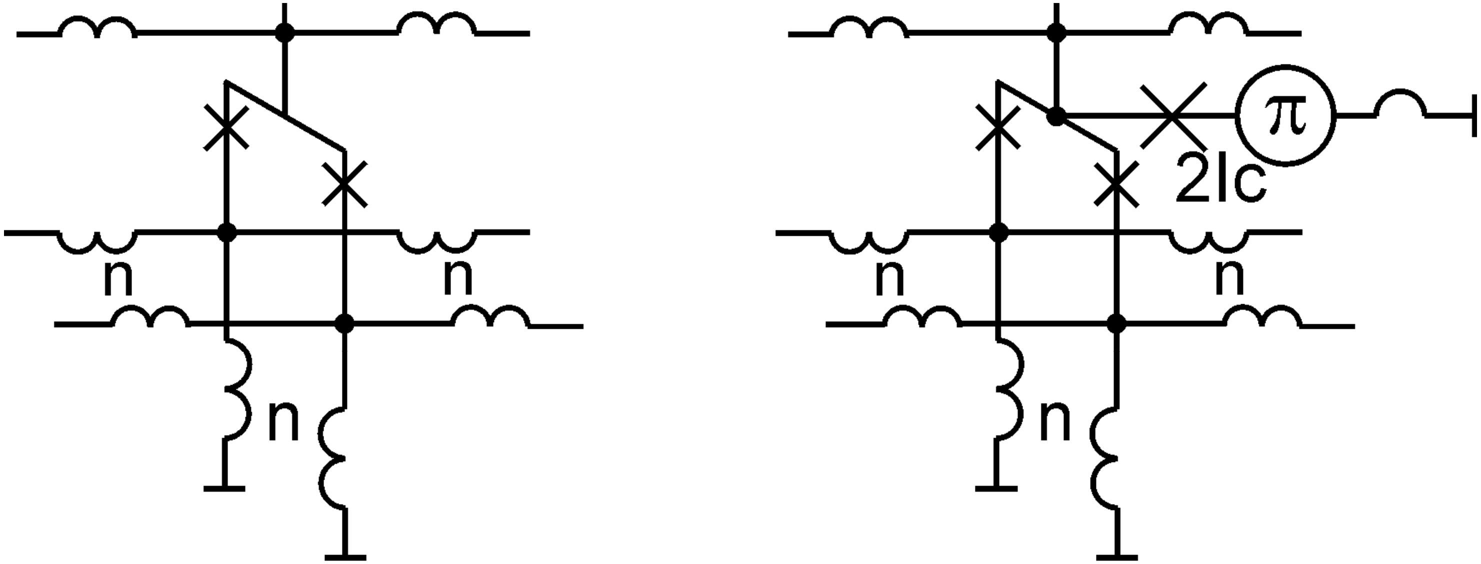
Possible implementation

Explanations taken from an old Landauer paper ===➔



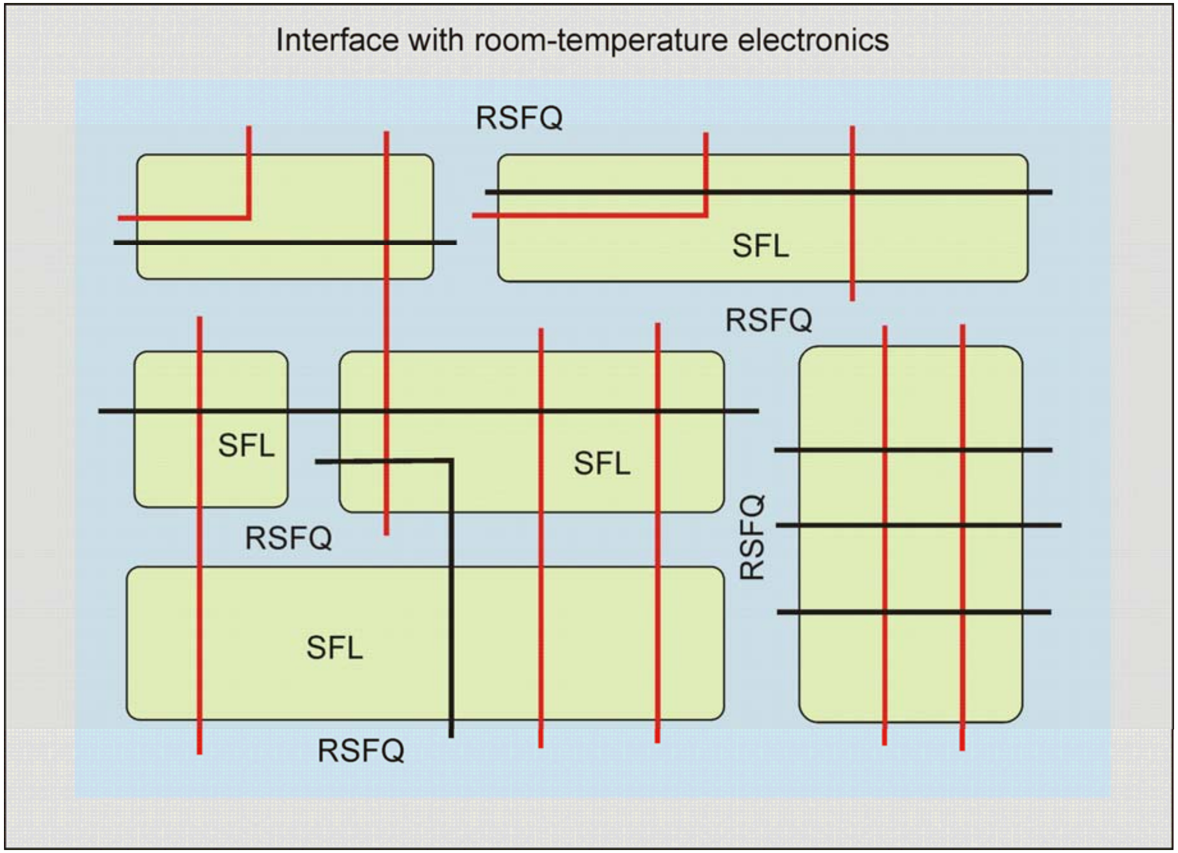
Coupled particles in time-dependent potential wells. In the transition from *a* to *b*, the information in the bistable well on the left sets the state of the one on the right. In the transition from *b* to *c* the well on the left is restored to a monostable state and is ready to receive new information.

Prospective nSQUID with π Junction as a Basis for Lumped Reversible Circuitry



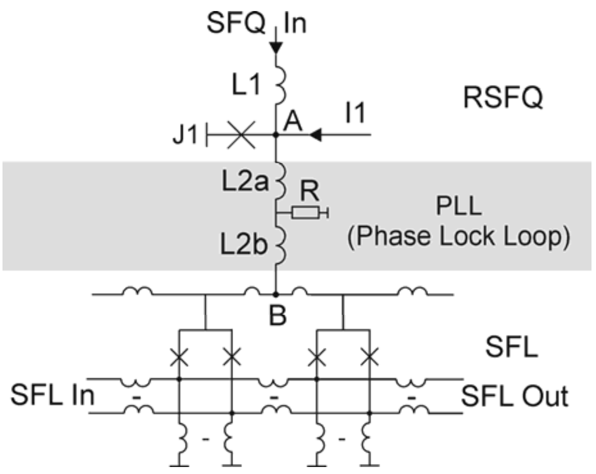
nSQUID current returns to the ground via other nSQUIDs. It means that nSQUID devices are inherently distributed. There is at leat one option to make lumped nSQUID circuits. It is known that π-junction is similar to conventional Josephson junctions but it generates current with opposite direction. nSQUID composed of conventional and π junctions would have similar a similar dependence of the energy profile on the clock phase but it will generate much lower current. This is because most of “conventional” current is compensated by π current.

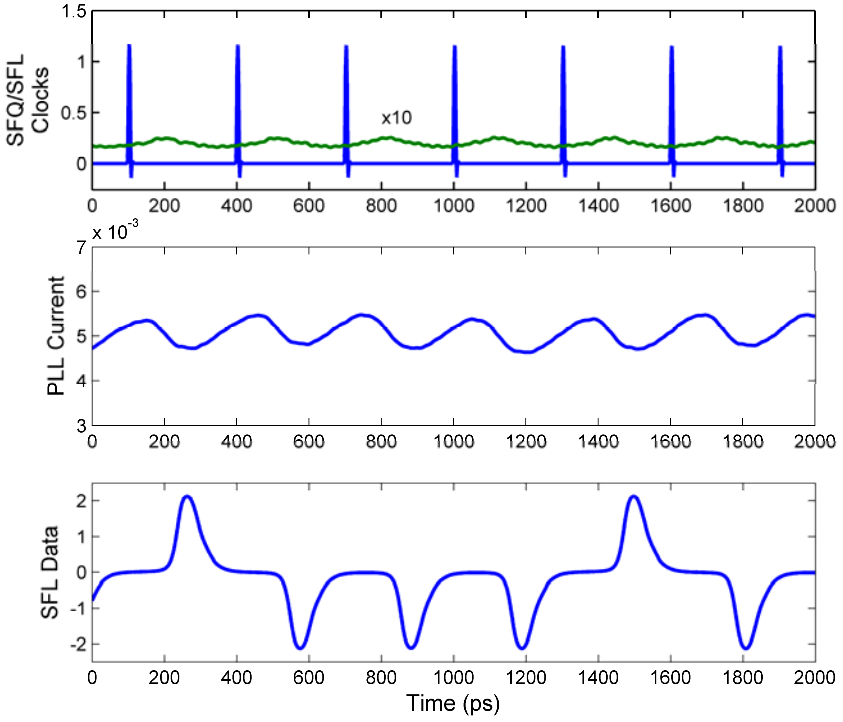
General Structure of a Composite Reversible (SFL) and eRSFQ Digital Circuitry



Currently reversible circuits look quite exotic. We suggest that the first reversible circuits should be delivered with the “mandatory” RSFQ or eRSFQ interface. As a result, reversible components will be invisible for high-level engineering and architectural errorts.

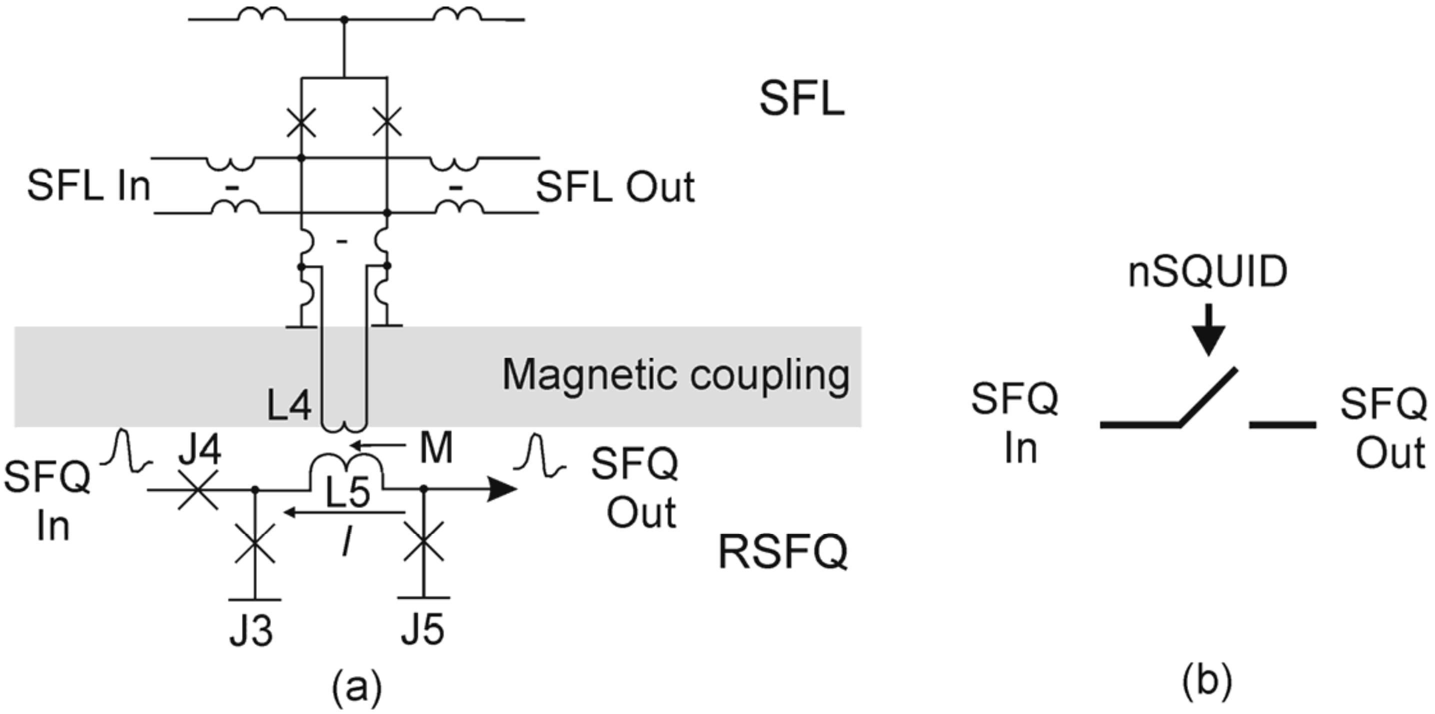
Synchronization of nSQUID circuitry





In fact, we need only a low-pass filter to smooth SFQ pulses. Numerical simulations are made by J. Ren.

RSFQ Read Out of nSQUID Data



Details for clocked or digital SQUID (lower part in the sketch) could be found in V. Semenov, IEEE Trans. On Appl. Supercond., vol. 13, pp. 747-50, 2003

Conclusion

- It looks that we are able to provide experimental support for the theory of reversible computing developed by R. Landauer and C. Bennett.
- Experimentation with reversible circuits could bring several benefits.
- The technology could be practical if, indeed, the energy dissipation will be a really critical issue. Two evident examples are: small digital circuits operating at sub Kelvin temperatures and really huge digital systems, where fore some reason the cost is less significant factor than the energy dissipation.
- Many features of nSQUIDs are quite similar to those of qubits. From academic point of view it would be exiting to run a competition for the lowest possible energy dissipation. Quantum effects will play important role when/if the energy dissipation is 10^{-4} of k_BT. In this case a few nSQUIDs could be renamed into qubits and there is a chance that such circuits could be reconstructed into a quantum computer.

Acknowledgements

- **Our projects were relatively small. For example, our last year budget related with reversible computing was $47 K. In fact, we were much richer because of many different kinds of support.**
- **First, we like to mention unique but inexpensive or occasionally free fabrication of superconducting circuits at HYPRES, Inc. We received also a lot of help from Oleg Mukhanov, S. Tolpygo, A. Kirichenko, T. Filippov and D. Gupta.**
- **Second, we thank for ONR support (Deborah VanVechten). In particular we have been funded for the development of an advanced (active) magnetic shielding. The advance shielding is vitally important for experimentation with reversible circuits.**
- **I wish to mentioned help from IBM Yorktown Heights people. In particular, frequent discussions with S. Rylov and A. Rylyakov.**
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- **But of course nothing could be possible unless ARO contract number W911NF-06-1-217 opened “Pandora box” of reversible computing.**