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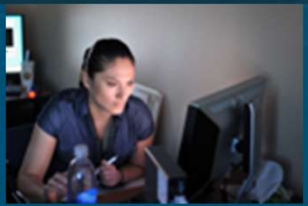
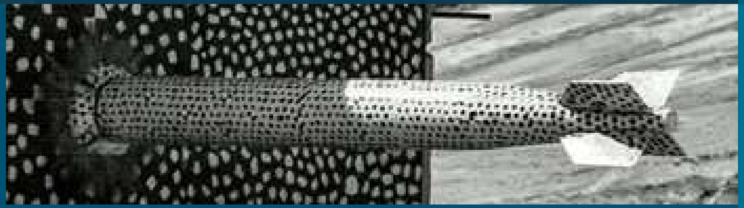
4th Workshop on Quantum and Classical Cryogenic Devices, Circuits, and Systems
Kyoto, Japan, September 28–30, 2022

Sandia National Laboratories

The Asynchronous Ballistic Approach to Reversible Superconducting Logic





Friday, September 30th, 2022

Michael P. Frank, Center for Computing Research

with Rupert Lewis (Quantum Phenomena Dept.)

Approved for public release, SAND2022-____ C

Abstract

(hide during talk)

The Asynchronous Ballistic Approach to Reversible Superconducting Logic

Michael P. Frank[1]
[1]*Center for Computing Research, Sandia National Laboratories, PO Box 5800, Albuquerque, NM 87185-1322, USA*
e-mail: mpfrank@sandia.gov

The two major lines of investigation towards the engineering of practical reversible computing hardware both began in the late 1970s, with Likharev's earliest paper on his adiabatic superconducting Parametric Quantron circuit in 1977, and Fredkin and Toffoli's proposal to use the underdamped, ballistic dynamics of switched LC circuits in 1978. The former approach evolved over the years to the point where today we have fairly well-developed technologies for adiabatic reversible computing in both superconductor and semiconductor platforms, but the alternative ballistic approach to reversible computing is less advanced to date. Its development has been held back in large part by concerns with maintaining synchronous behavior and avoiding chaotic instabilities. Since 2016, Sandia has been investigating a novel approach towards ameliorating these difficulties via the use of a *locally asynchronous* model of ballistic reversible computing in superconducting circuits, which is insensitive to small uncertainties in the arrival times of different inputs to a given circuit. In this talk, we will review the key concepts behind this new approach, the progress that has been made to date by various groups that is relevant to its development, and the outstanding research challenges that still remain to be addressed

Contributors to our Reversible Computing research program

Sandia National Laboratories

- Full group of recent staff at Sandia:
  - Michael Frank (Cognitive & Emerging Computing)
  - Robert Brocato (RF MicroSystems) – now retired
  - David Henry (MESA Hetero-Integration)
  - Rupert Lewis (Quantum Phenomena)
    - Terence "Terry" Michael Bretz-Sullivan
  - Nancy Missert (Nanoscale Sciences) – now retired
    - Matt Wolak (now at Northrop-Grumman)
  - Brian Tierney (Rad Hard CMOS Technology)

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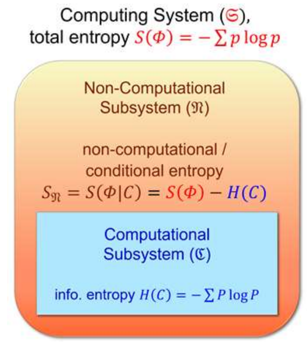
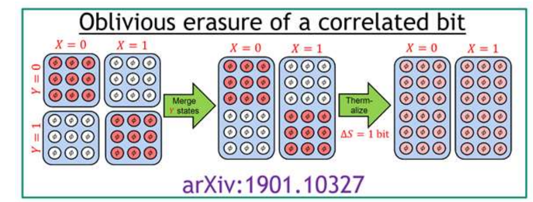
- Thanks are also due to the following colleagues & external research collaborators:
  - Karpur Shukla (CMU → Flame U. → Brown U.)
    - In the lab of Prof. Jimmy Xu
  - Hannah Earley (Cambridge U. → startup)
  - Erik DeBenedictis (Sandia → Zettaflops, LLC)
  - Joseph Friedman (UT Dallas)
    - with A. Edwards, X. Hu, B.W. Walker, F. Garcia-Sanchezy, P. Zhou, J.A.C. Incorviaz, A. Paler
  - Kevin Osborn (LPS/JQI)
    - Liuqi Yu, Ryan Clarke, Han Cai
  - Steve Kaplan
  - Rudro Biswas (Purdue)
    - Dewan Woods & Rishabh Khare
  - Tom Conte (Georgia Tech/CRNCH)
    - Anirudh Jain, Gibran Essa
  - David Guéry-Odelin (Toulouse U.)
  - FAMU-FSU College of Engineering:
    - Sastry Pamidi (ECE Chair) & Jerris Hooker (Instructor)
    - 2019-20 students:
      - Frank Allen, Oscar L. Corces, James Hardy, Fadi Matloob
    - 2020-21 students:
      - Marshal Nachreiner, Samuel Perlman, Donovan Sharp, Jesus Sosa

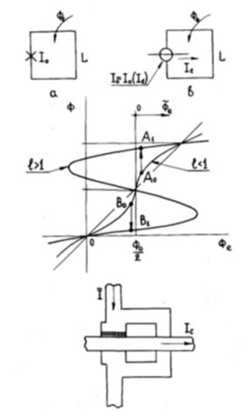
Talk Abstract/Outline

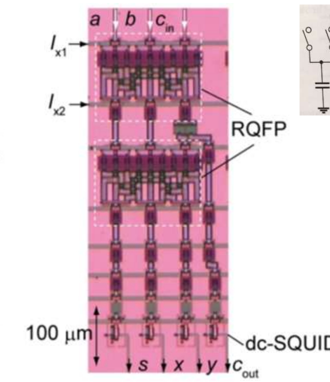


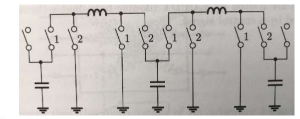


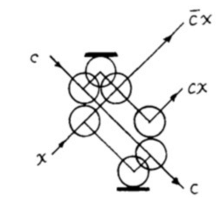
The Asynchronous Ballistic Approach to Reversible Superconducting Logic

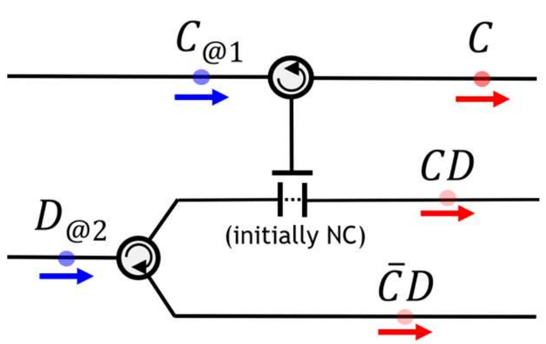
- Why Reversible Computing?
  - Relevant classic results in the thermodynamics of computing (since generalized to quantum case)
- Two major types of approaches to reversible computing in superconducting circuits:
  - *Adiabatic* approaches – Well-developed today.
    - Likharev's *parametric quantron* (1977); more recent QFP tech (YNU & collabs.) w. substantial demo chips.
  - *Ballistic* approaches – Much less mature to date.
    - Fredkin & Toffoli's early concepts (1978–'81); much more recent work at U. Maryland, Sandia, UC Davis
- **Focus of talk:** The relatively new *asynchronous* ballistic approach to RC in SCE
  - Addresses concerns w instability of the synchronous ballistic approach
  - Potential advantages of asynchronous ballistic RC (vs. adiabatic approaches)
  - Relevant progress that has been made by various groups to date
  - Major outstanding research challenges that remain to be addressed at this time

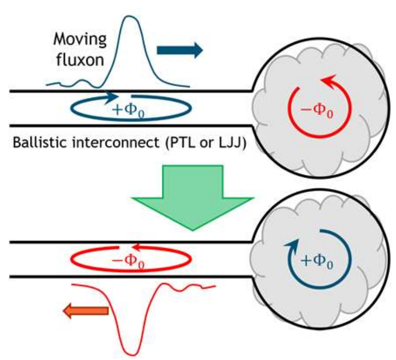


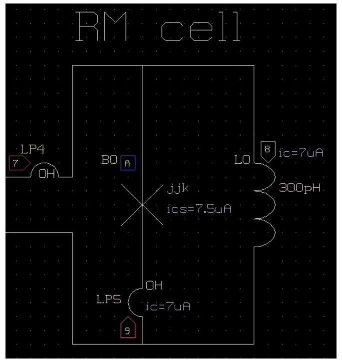


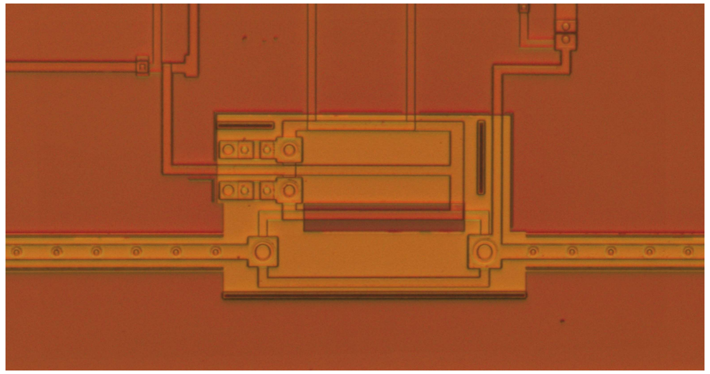


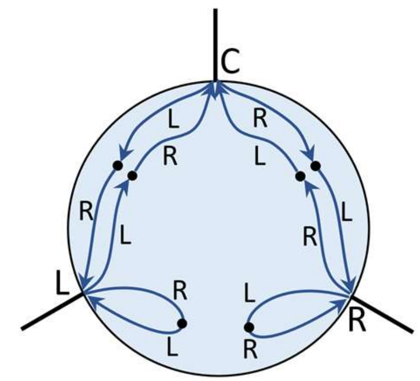








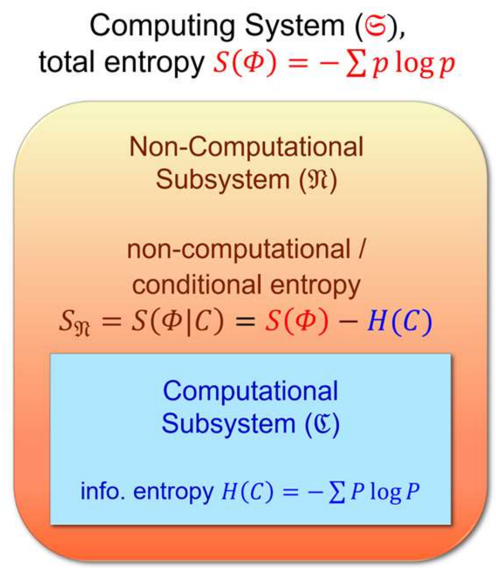




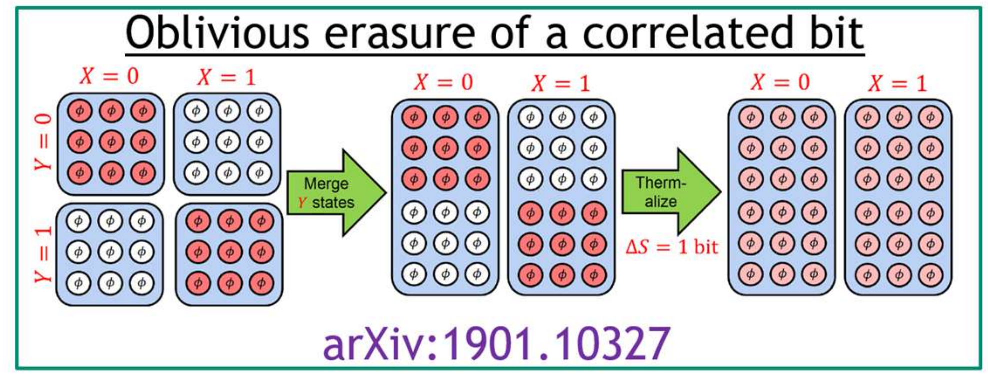
Why Reversible Computing?
Thermodynamics of computing: Relevant classic results

Based on the pioneering historical insights of Landauer & Bennett…

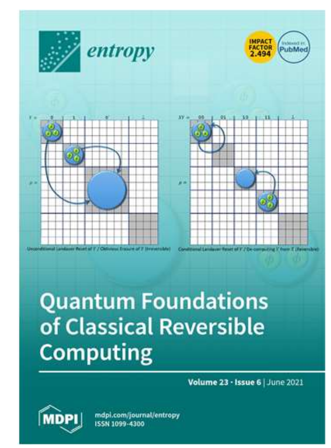
1. Fundamental Theorem of the Thermodynamics of Computing →
   - Unification of physical and information-theoretic entropy.
     - Implies interconvertibility of computational and non-computational entropy.
2. Landauer's Principle (proper) →
   - Loss of known/correlated computational information to a thermal environment transforms it into *new* physical entropy.
3. Conventional digital architectures (which discard correlated information all the time) have a *fundamental* efficiency limit…
   - $\geq kT \ln 2$ energy dissipation per bit of information loss.
     - Actual losses per bit erased in practical designs tend to be at least 10s–1000s of kT.
4. Alternative *reversible* digital architectures which transform states 1:1 can (at least in principle) avoid the Landauer limit.
   - There is no known fundamental efficiency limit for reversible machines.



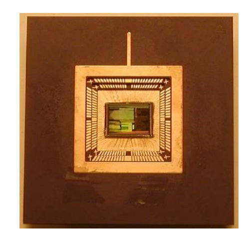
$$P(c_j) = \sum_{\phi_i \in c_j} p(\phi_i)$$



Quantum generalizations of classic results surveyed in M. Frank & K. Shukla, doi:10.3390/e23060701 —



Pendulum adiabatic processor (MIT '99)



The two major approaches to reversible computing
Both relevant in superconducting electronics

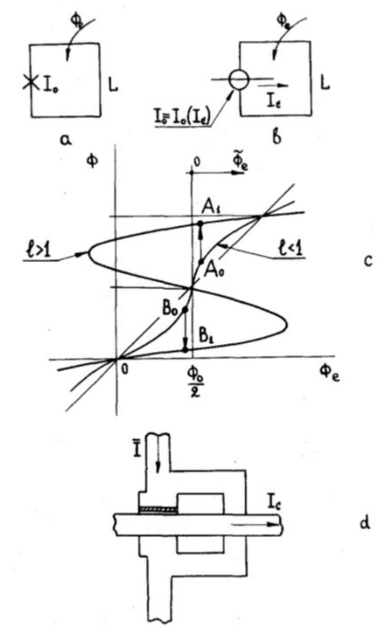
***Adiabatic* approaches** – based on *gradually* transforming a device's potential energy surface

- General method suggested in Landauer's original (1961) paper.
  - By definition, transitions are *slow* compared to the natural relaxation timescale of the device.
- First historical example of an engineered fully adiabatic electronic logic cell:
  - Likharev's *parametric quantron* (1977) – Use a *control current* I_c to raise/lower the potential energy barrier between loop states.
- Modern AQFP/RQFP technology from YNU has a similar spirit, but is much more well-developed.

***Ballistic* approaches** – based on *ballistic* dynamics & *elastic* interactions between DOFs

- Assumes relatively slight coupling between dynamical DOFs and the thermal environment…
  - Interactions happen *fast* relative to that coupling, so there isn't *time* for the dynamical excited state to relax thermally – dynamical energy largely *conserved* in the DOFs of interest.
- Early electronic & mechanical concepts proposed by Fredkin & Toffoli:
  - Early electronic concept (1978) as an underdamped LC circuit with idealized switches…
  - Simple mechanical thought experiment (1981)… "Billiard Ball Model"
- But, almost no engineering development of this approach from 1980 – 2010!
  - Why? The original concept appeared to have intractable issues w. synchronization / chaotic instabilities…

10.1109/TMAG.1977.1059351:



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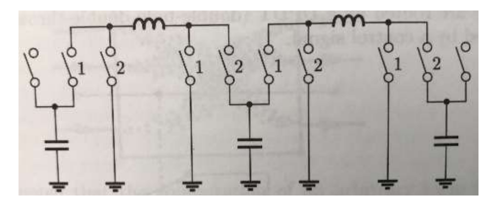

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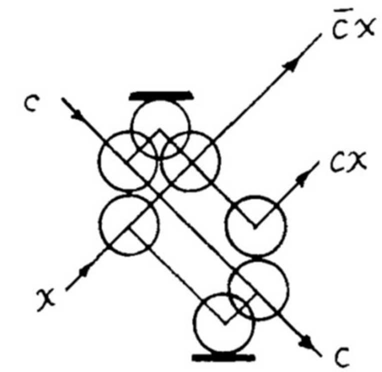


Ballistic Reversible Computing

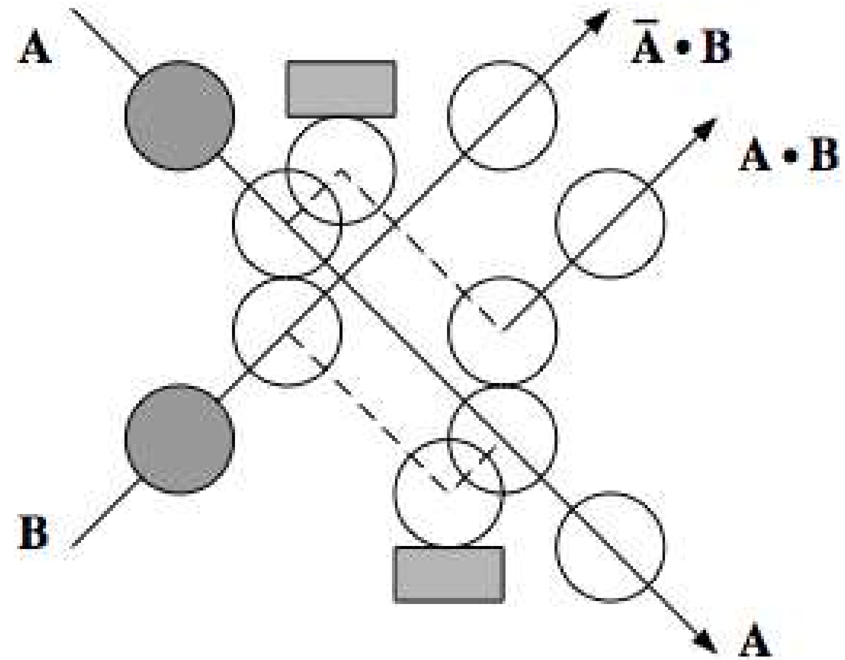
Can we envision reversible computing as a *deterministic* elastic interaction process?

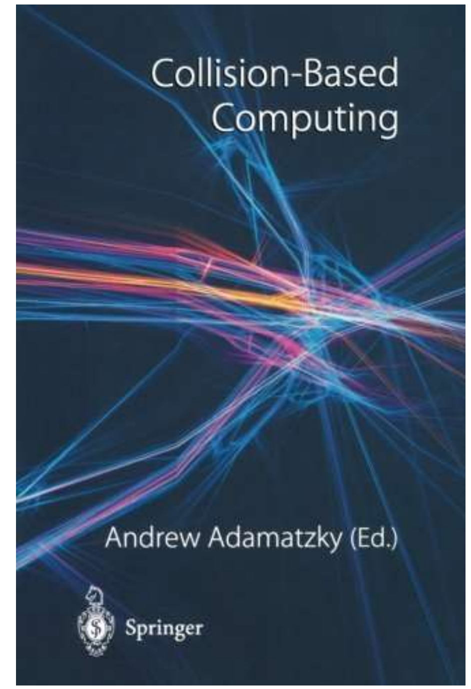
Historical origin of this concept:

- Fredkin & Toffoli's *Billard Ball Model* of computation ("Conservative Logic," IJTP 1982).
  - Based on elastic collisions between moving objects.
  - Spawned a subfield of "collision-based computing."
    - Using localized pulses/solitons in various media.

No power-clock driving signals needed!

- Devices operate when data signals arrive.
- The operation energy is carried by the signal itself.
  - Most of the signal energy is preserved in outgoing signals.





However, all (or almost all) of the existing design concepts for ballistic computing invoke implicitly *synchronized* arrivals of ballistically-propagating signals…

- Making this work in reality presents some serious difficulties, however:
  - Unrealistic in practice to assume precise alignment of signal arrival times.
    - Thermal fluctuations & quantum uncertainty, at minimum, are always present.
  - Any relative timing uncertainty leads to chaotic dynamics when signals interact.
    - Exponentially-increasing uncertainties in the dynamical trajectory.
  - Deliberate *re*synchronization of signals whose timing relationship is uncertain incurs an inevitable energy cost.

Can we come up with a new ballistic model that avoids these problems?

Ballistic Asynchronous Reversible Computing (BARC)

Problem: Conservative (dissipationless) dynamical systems generally tend to exhibit chaotic behavior…

- This results from direct nonlinear *interactions* between multiple continuous dynamical degrees of freedom (DOFs), which amplify uncertainties, exponentially compounding them over time…
  - *E.g.*, positions/velocities of ballistically-propagating "balls"
    - Or more generally, any localized, cohesive, momentum-bearing entity: Particles, pulses, quasiparticles, solitons…

Core insight: In principle, we can greatly reduce or eliminate this tendency towards dynamical chaos…

- We can do this simply by *avoiding* any direct interaction between continuous DOFs of different ballistically-propagating entities

Require localized pulses to arrive *asynchronously*—and furthermore, at clearly distinct, *non-overlapping* times

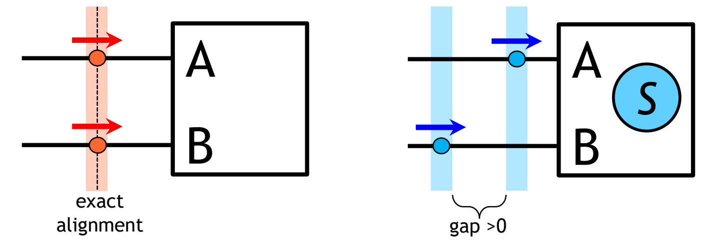
- Device's dynamical trajectory then becomes *independent* of the precise (absolute *and* relative) pulse arrival times
  - As a result, timing uncertainty per logic stage can now accumulate only *linearly*, not exponentially!
    - Only relatively occasional re-synchronization will be needed
- For devices to still be capable of doing logic, they must now maintain an internal discrete (digitally-precise) state variable—a stable (or at least metastable) stationary state, *e.g.*, a ground state of a well

No power-clock signals, unlike in adiabatic designs!

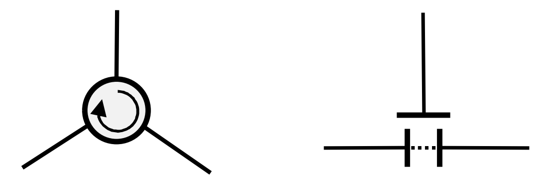
- Devices simply operate whenever data pulses arrive
- The operation energy is carried by the pulse itself
  - Most of the energy is preserved in outgoing pulses
    - Signal restoration can be carried out incrementally

Goal of current effort at Sandia: Demonstrate BARC principles in an implementation based on fluxon dynamics in SuperConducting Electronics (SCE)

(BARCS effort)

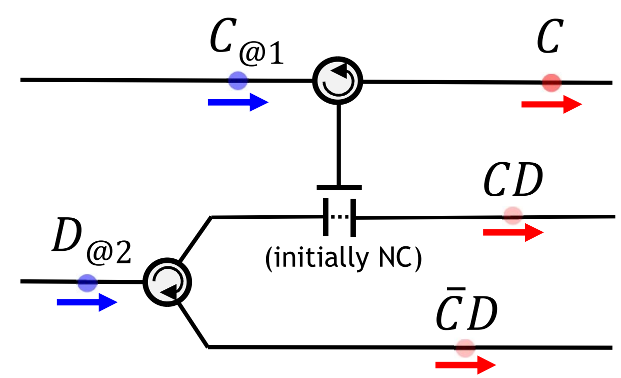


Synchronous Ballistic Asynchronous Ballistic



Rotary (Circulator) Toggled Barrier

Example BARC device functions



Example logic construction

Simplest Fluxon-Based (bipolarized) BARC Function

One of our early tasks: Characterize the simplest nontrivial BARC device functionalities, given a few simple design constraints applying to an SCE-based implementation, such as:

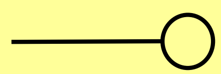
- (1) Bits encoded in fluxon polarity; (2) Bounded planar circuit conserving flux; (3) Physical symmetry.

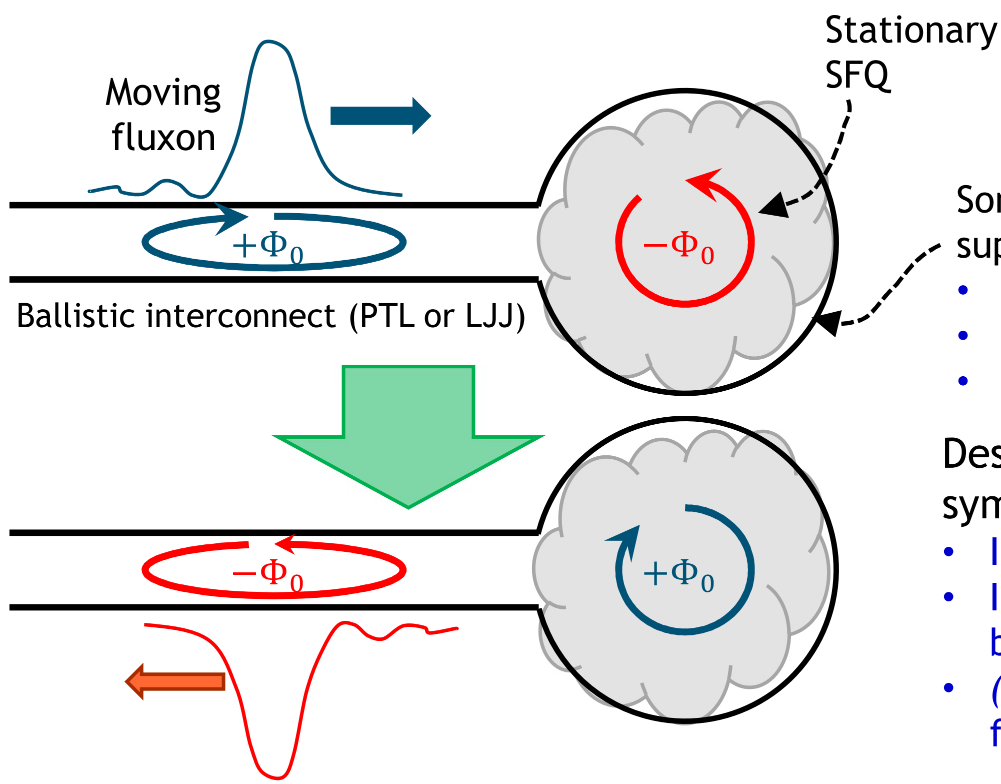
Determined through theoretical hand-analysis that the simplest such function is the ***1-Bit, 1-Port Reversible Memory Cell (RM):***

- Due to its simplicity, this was then the preferred target for our subsequent detailed circuit design efforts…

RM Transition Table

Input Syndrome		Output Syndrome
+1(+1)	→	(+1)+1
+1(−1)	→	(+1)−1
−1(+1)	→	(−1)+1
−1(−1)	→	(−1)−1

RM icon: 



Some planar, unbiased, reactive SCE circuit w. a continuous superconducting boundary

- *Only* contains L's, M's, C's, and *unshunted* JJs
- Junctions should mostly be *subcritical* (avoids R_N)
- Conserves total flux, approximately nondissipative

Desired circuit behavior (NOTE: conserves flux, respects T symmetry & logical reversibility):

- If polarities are opposite, they are swapped (shown)
- If polarities are identical, input fluxon reflects back out with no change in polarity (not shown)
- *(Deterministic) elastic 'scattering'* type interaction: Input fluxon kinetic energy is (nearly) preserved in output fluxon

RM—First working (in simulation) implementation!

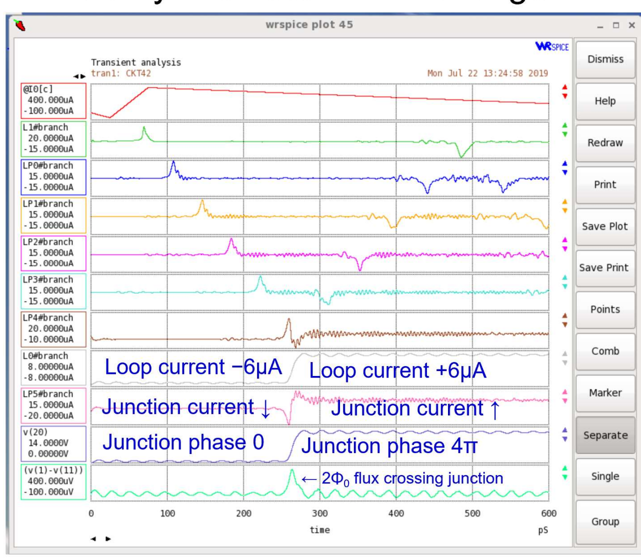
Erik DeBenedictis: “Try just strapping a JJ across that loop.”
- This actually works!

“Entrance” JJ sized to = about 5 LJJ unit cells (~1/2 pulse width)
- I first tried it twice as large, & the fluxons annihilated instead…
  - “If a 15 μA JJ rotates by 2π, maybe ½ that will rotate by 4π” 🤔

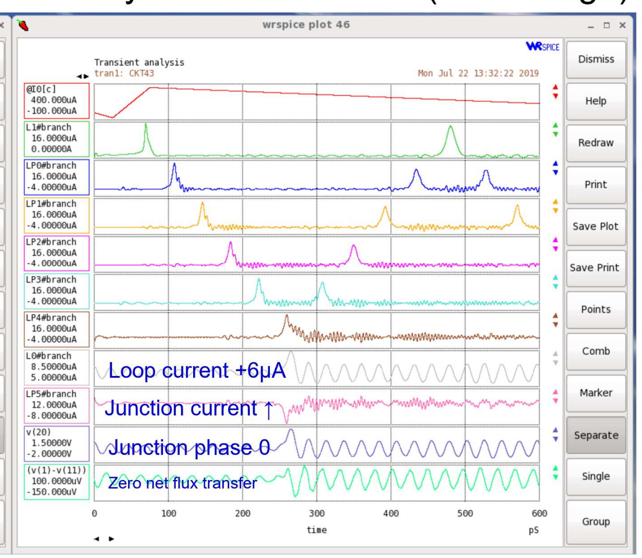
Loop inductor sized so ±1 SFQ will fit in the loop (but not ±2)
- JJ is sitting a bit below critical with ± 1

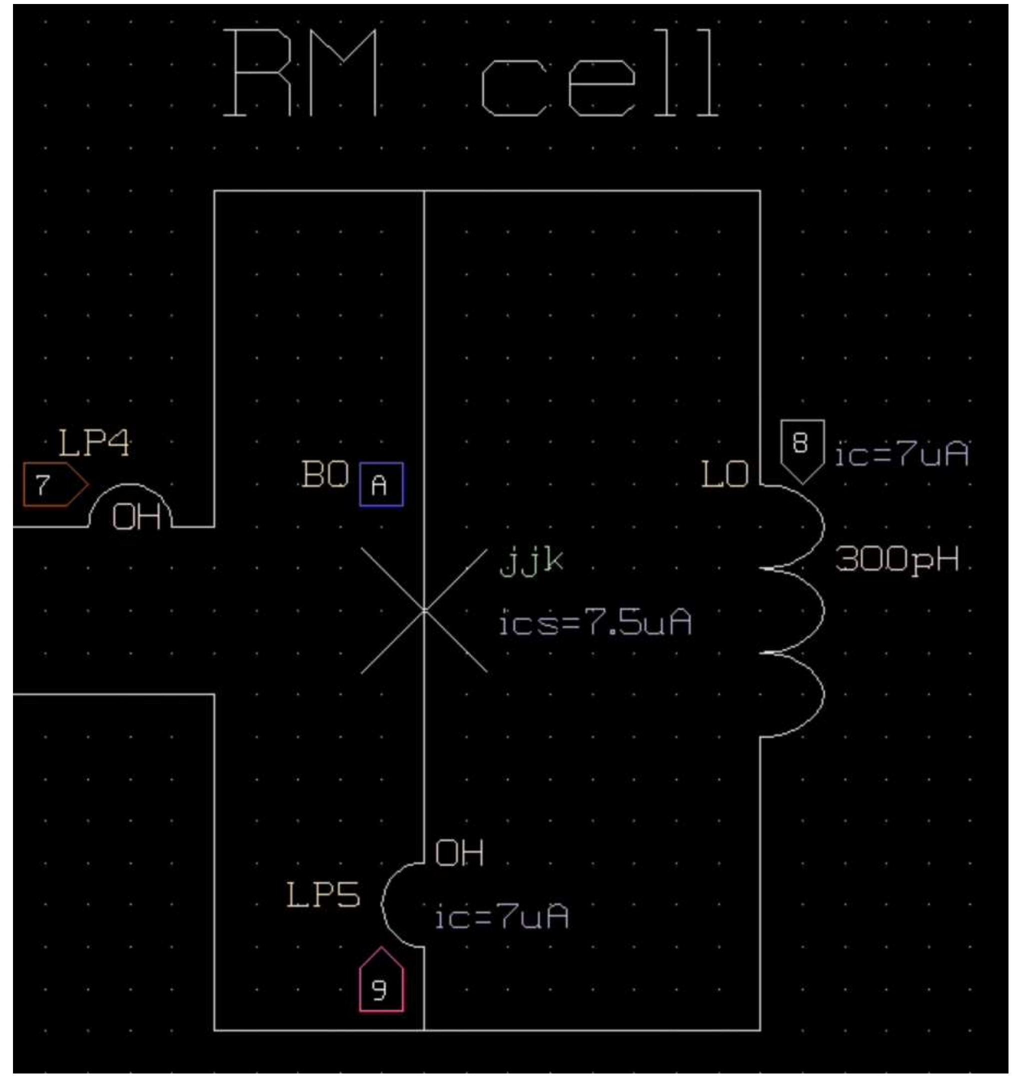
WRspice simulations with ±1 fluxon initially in the loop
- Uses `ic` parameter, & `uic` option to `.tran` command
  - Produces initial ringing due to overly-constricted initial flux
    - Can damp w. small shunt *G*

Polarity mismatch → Exchange



Polarity match → Reflect (=Exchange)

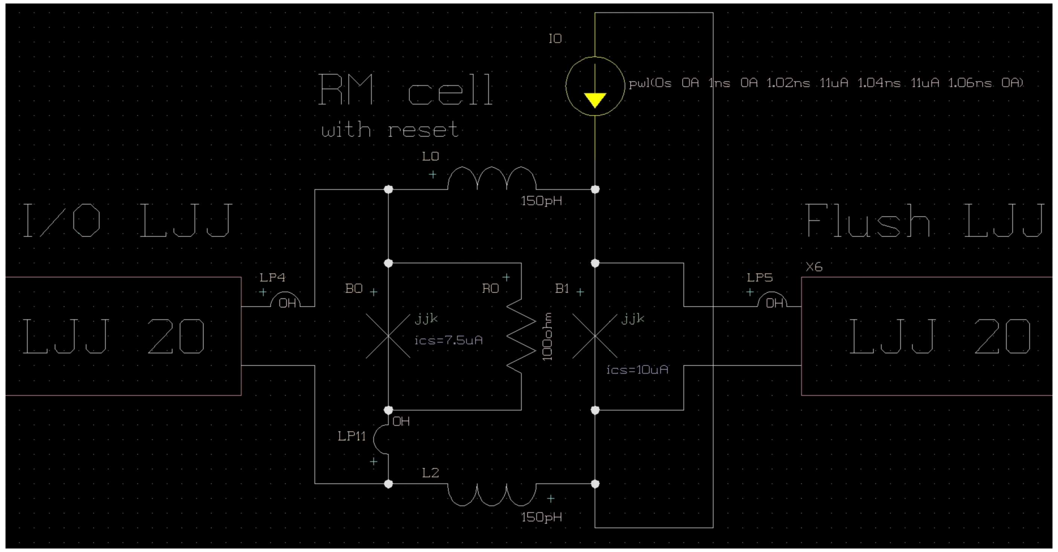


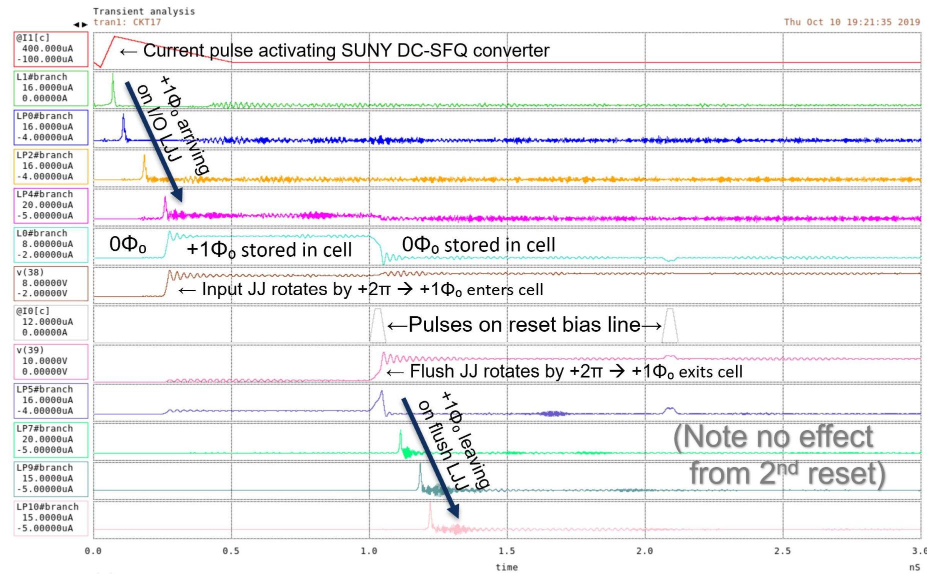


Resettable version of RM cell—Designed & Fabricated!

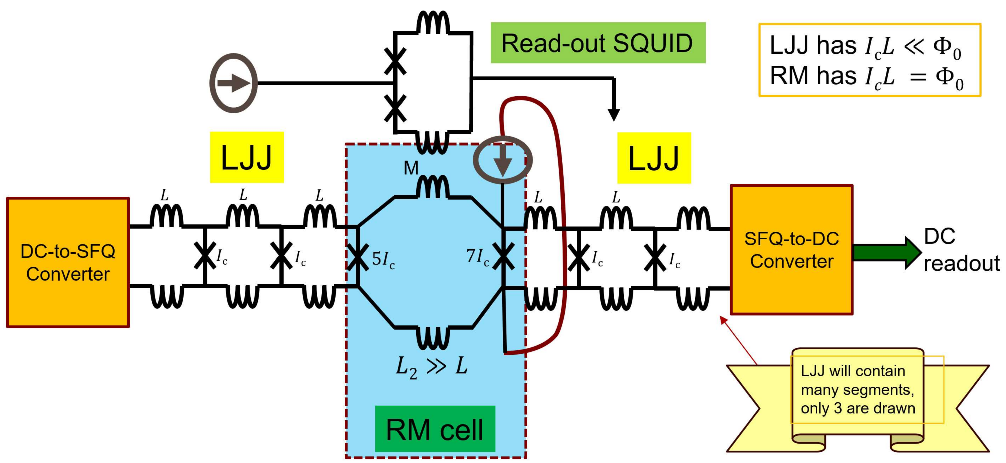
Apply current pulse of appropriate sign to flush the stored flux (the pulse here flushes out positive flux)

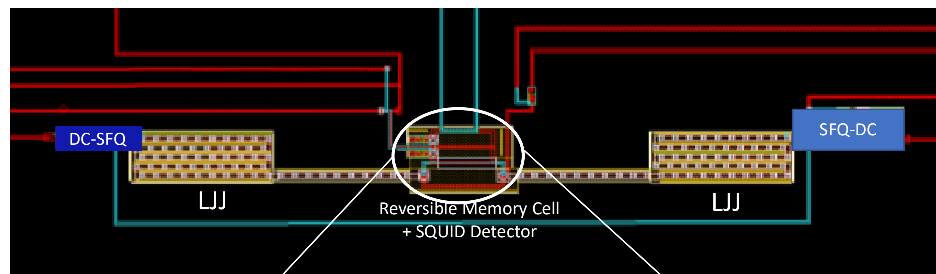
- To flush either polarity → Do both (±) resets in succession

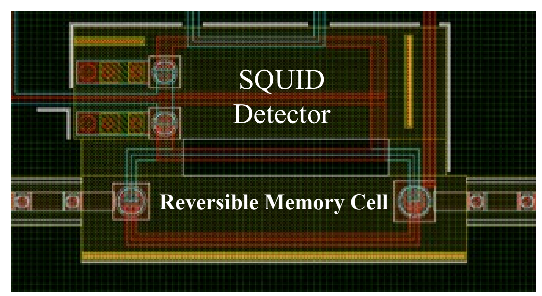




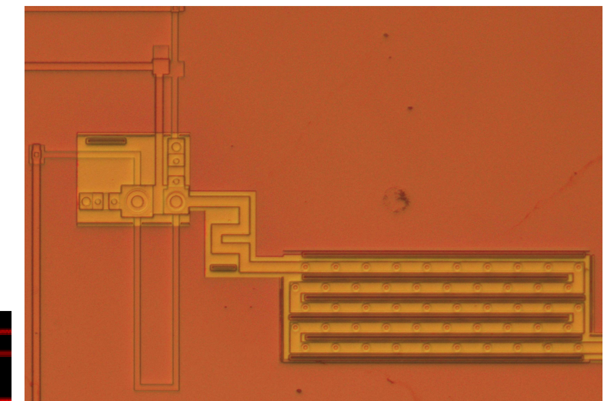
Fabrication at SeeQC with support from ACI



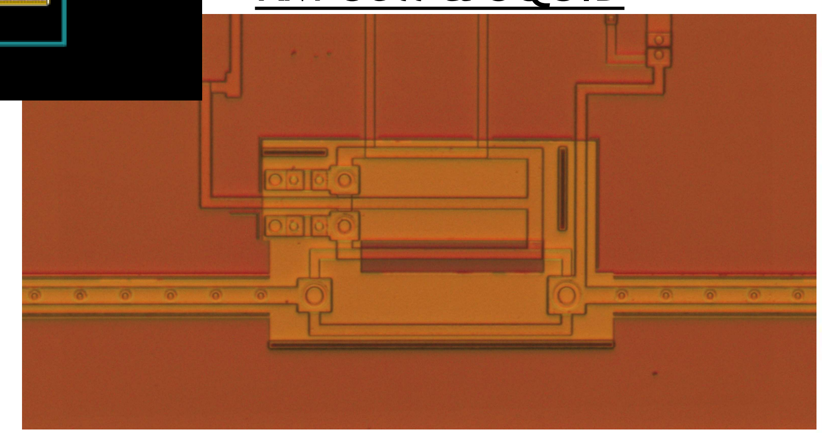




DC-SFQ & LJJ



RM Cell & SQUID



Overview of Some Recent Progress

BARC Element Classification and Characterization →

RM Cell Testing Efforts

Exploration of Novel Circuits
- Multi-port RM cell

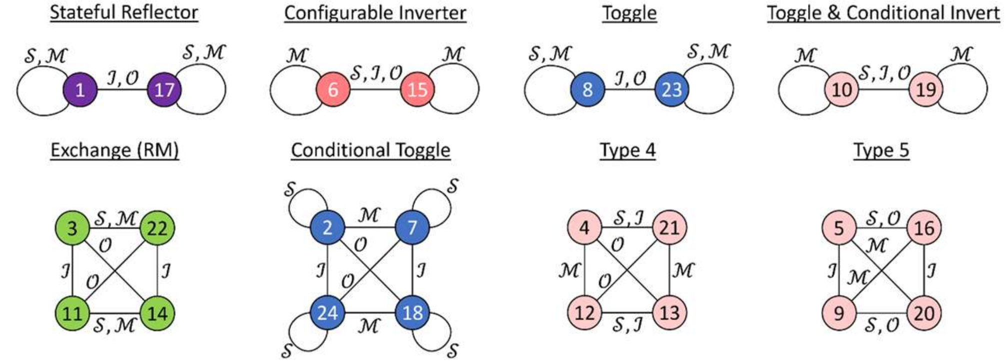
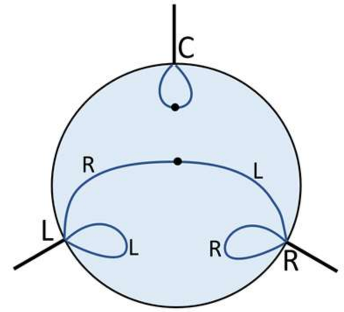


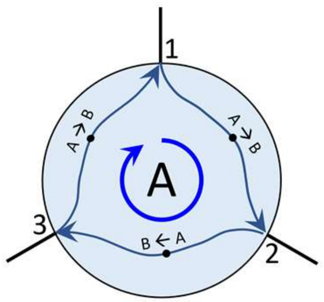
Table 1. Layer-cake architectural diagram of the BARC element-classification tool. Each module in the program only imports modules from lower layers in the stack.

Layer #	Module Names & Descriptions
4	**BARC** (top-level program)
3	**deviceType** – Classes of devices with given dimensions.
2	**deviceFunction** – Device with a specific transition function.
1	**pulseAlphabet** – Sets of pulse types. **symmetryGroup** – Equivalence classes of device functions. **transitionFunction** – Bijectively maps input syndromes to output syndromes.
0	**characterClass** – Defines a type of signal characters. **deviceDimensions** – Defines size parameters of devices. **dictPermuter** – Used to enumerate transition functions. **pulseType** – Identifies a specific type of pulse. **signalCharacter** – Identifies a type of I/O event (with pulse type & port). **state** – Identifies an internal state of a device. **stateSet** – Identifies a set of possible device states. **symmetryTransform** – Invertibly transforms a device function. **syndrome** – Identifies an initial or final condition for a device transition. **utilities** – Defines some low-level utility functions.

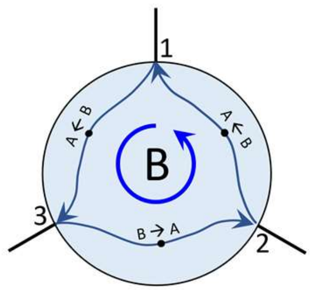
Polarized Controlled Flipping Diode



Polarized Neutral Toggle Rotary

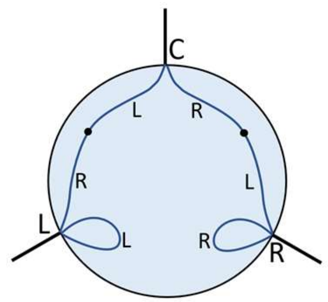


Behavior in Positive-Clockwise State (A)

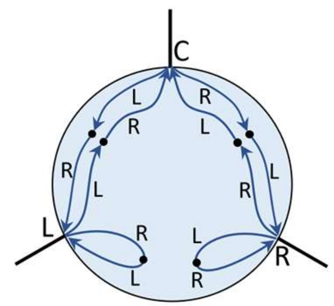


Behavior in Positive-Counterclockwise State (B)

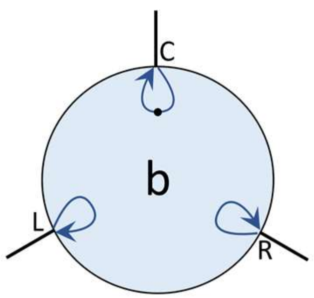
Polarized Throw Switch (Type A)



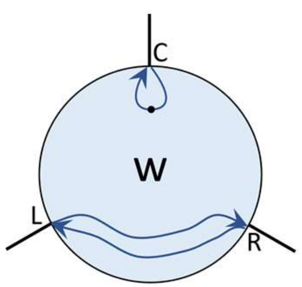
Polarized Throw Switch (Type B)



Polarized Toggle Controlled Barrier

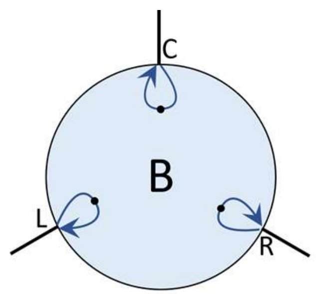


Behavior in Positive Barrier State (b)

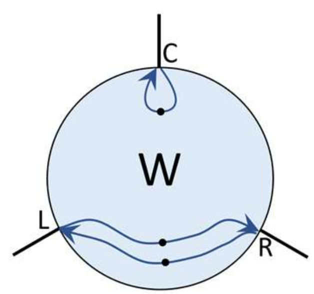


Behavior in Positive Wire State (w)

Polarized Knock-Twice Toggle Controlled Barrier



Behavior in Positive Barrier State (B)



Behavior in Positive Conducting State (W)

(All state behaviors shown are for + fluxons only; − fluxons interact oppositely w states)

Table 2. Summary of results of classification by BARC of the 600 nontrivial functions for 3-port, 2-state, flux-conserving, flux-neutral elements into 45 equivalence classes corresponding to distinct possible element behaviors.

Size of Equivalence Class	Number of Equivalence Classes	Number of Functions
2	1	2
4	1	4
6	9	54
12	23	276
24	11	264

```
Symmetry group #38 has 6 functions:
    Function #155.
    Function #340.
    Function #481.
    Function #285.
    Function #365.
    Function #185.

Example: Function #155 = [1]*3(L,R):
    1(L) -> (R)2
    1(R) -> (L)3
    2(L) -> (R)1
    2(R) -> (R)3
    3(L) -> (L)2
    3(R) -> (L)1

Function #155 has the following symmetry properties:
    It is D-dual to function #481
    It is S-dual to function #481
    It is E(1,2)-dual to function #340
    It is E(1,3)-dual to function #185
    It is E(2,3)-dual to function #481
    It R(-1)-transforms to function #365
    It R(1)-transforms to function #285
```

Fig. 2. Example description of an equivalence class as output by the BARC program.

Remaining Challenges for the BARCS effort

Empirical validation

Better understanding role of physical symmetries in element design

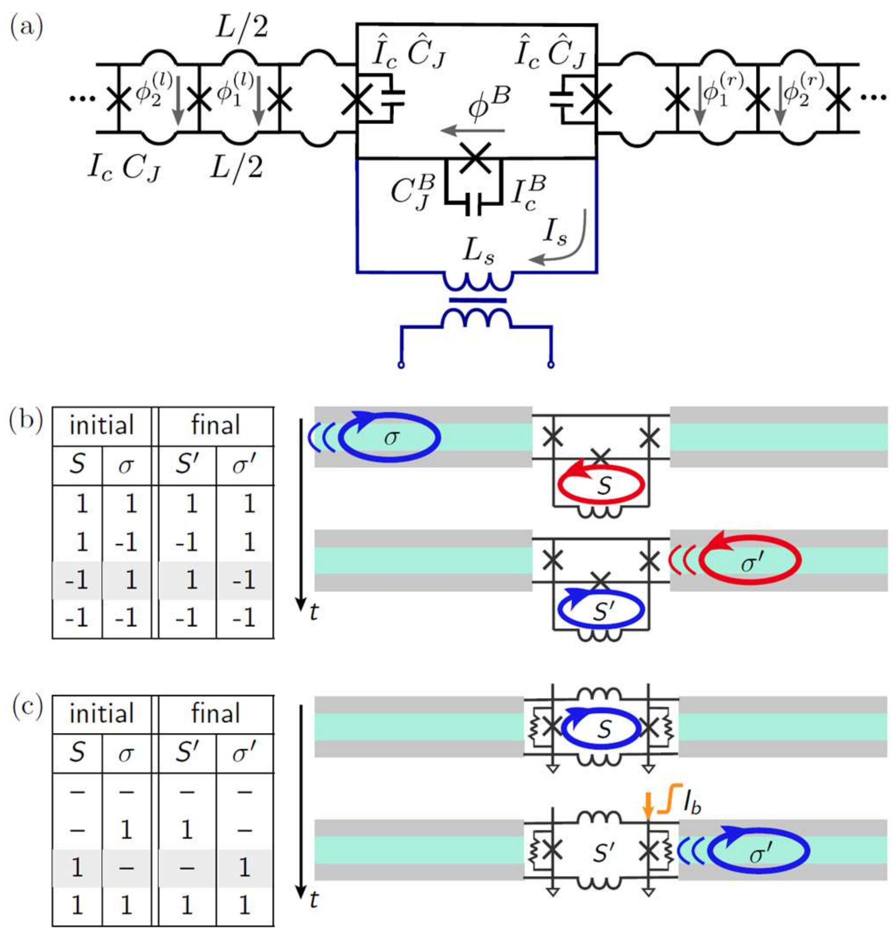
Identifying a universal set of elements that we also know how to implement!

Understanding the limits of energy efficiency of this approach

Much work remains to be done …

Ballistic Shift Registers

Work by Osborn & Wustmann, arxiv:2201.12999

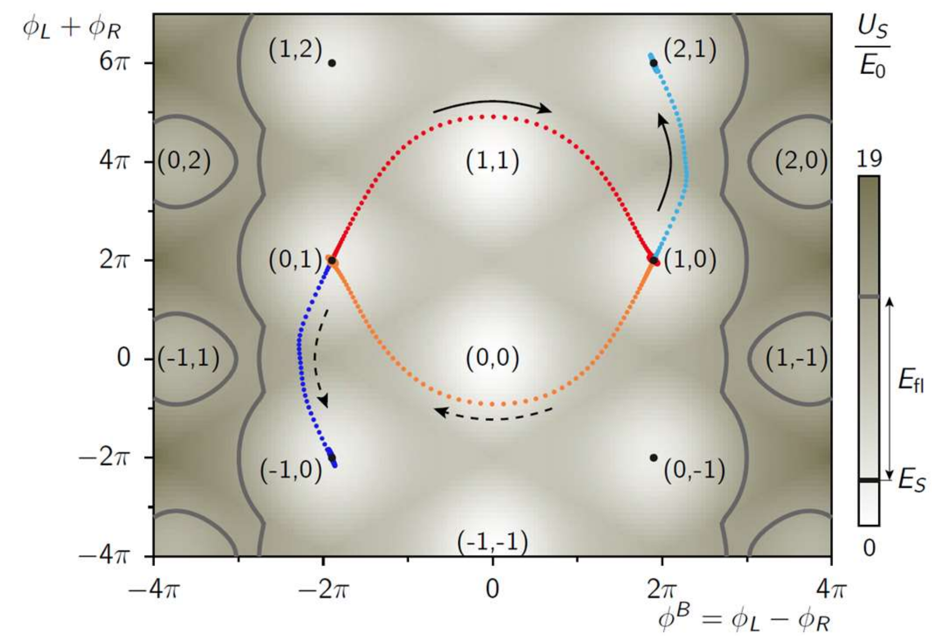


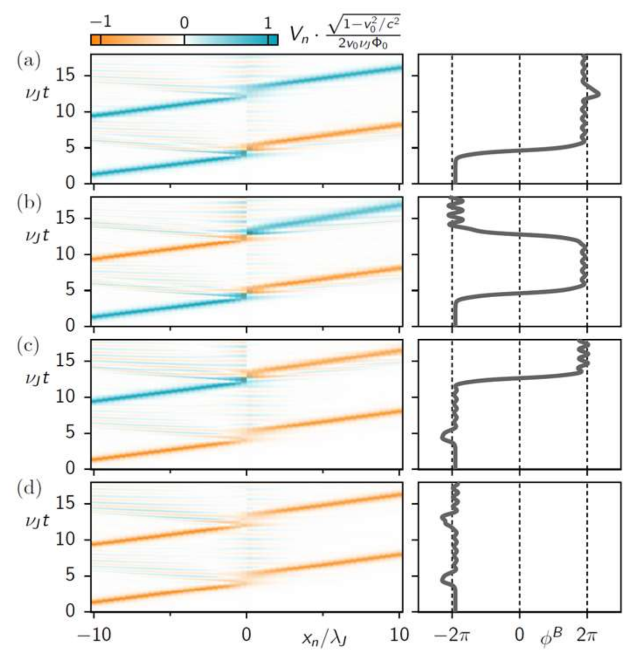
(b)

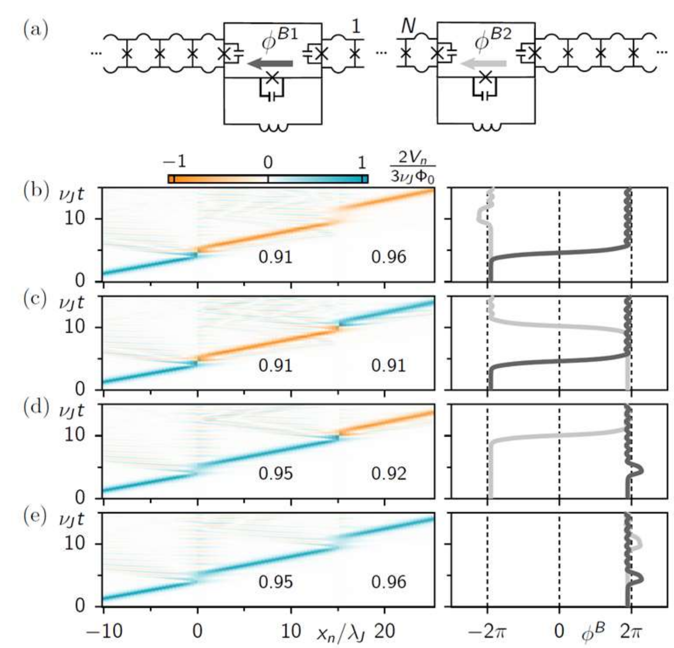
initial		final	
S	σ	S'	σ'
1	1	1	1
1	-1	-1	1
-1	1	1	-1
-1	-1	-1	-1

(c)

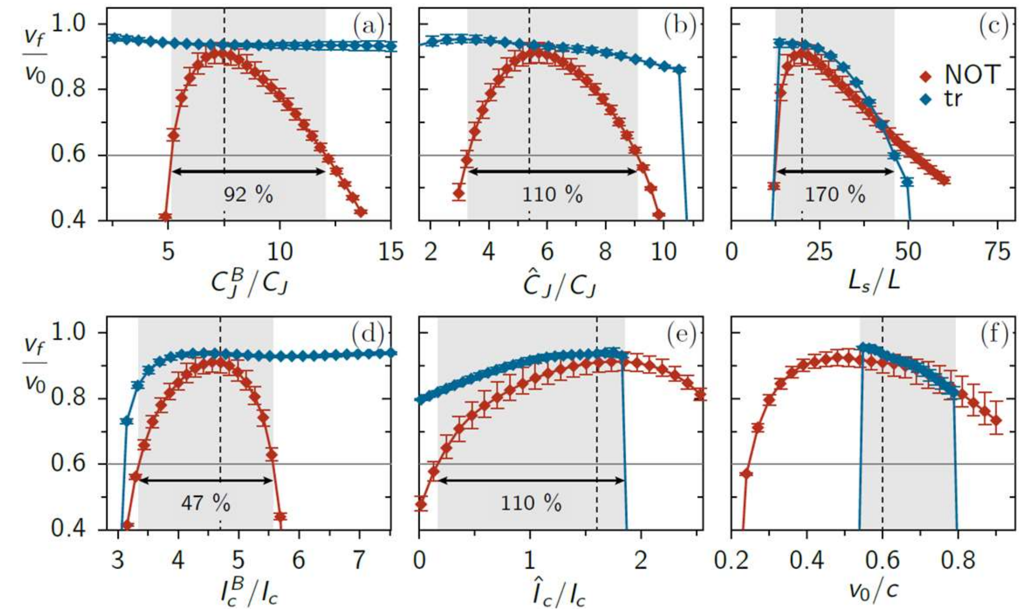
initial		final	
S	σ	S'	σ'
–	–	–	–
–	1	1	–
1	–	–	1
1	1	1	1

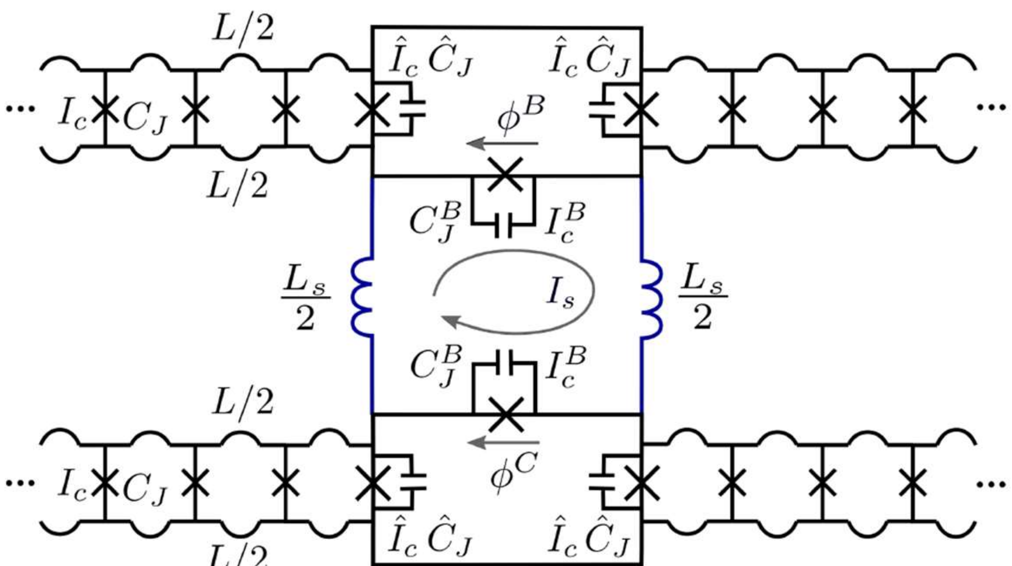


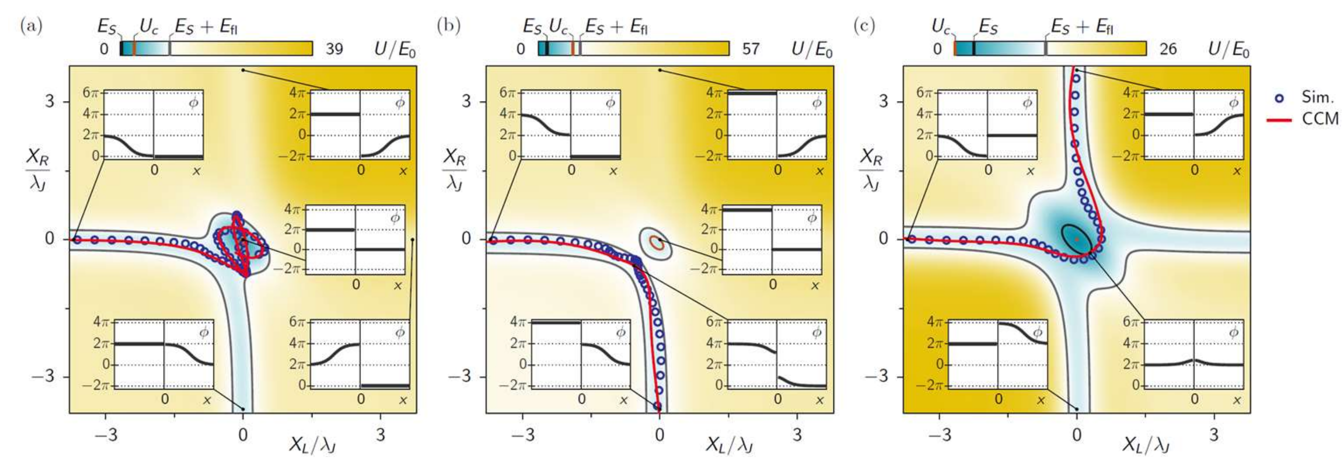




Ballistic Shift Registers, cont.

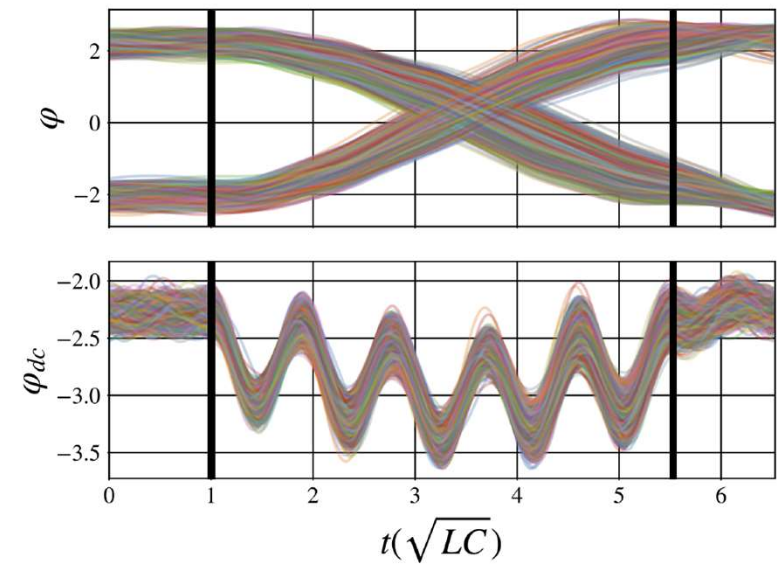


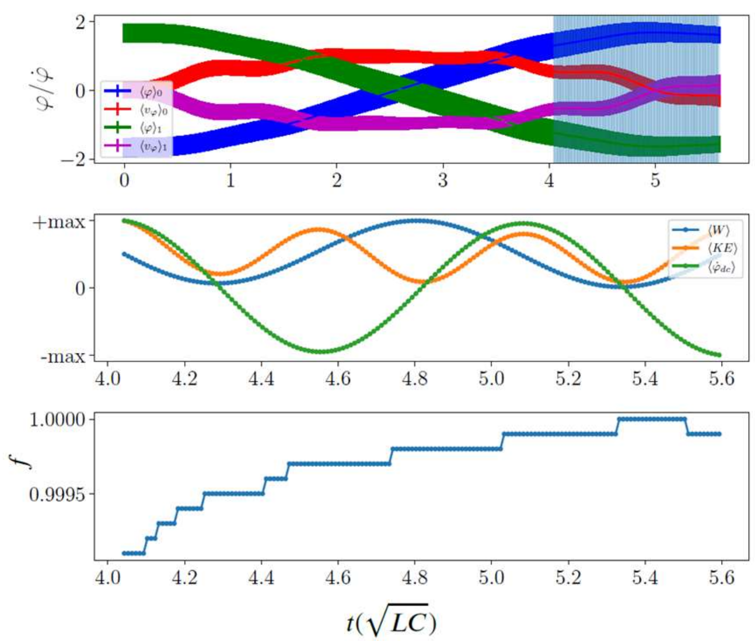


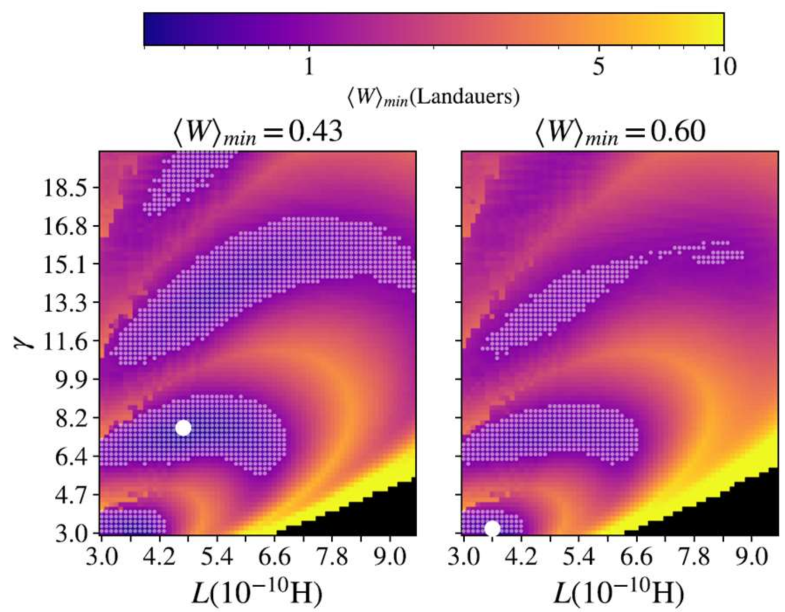


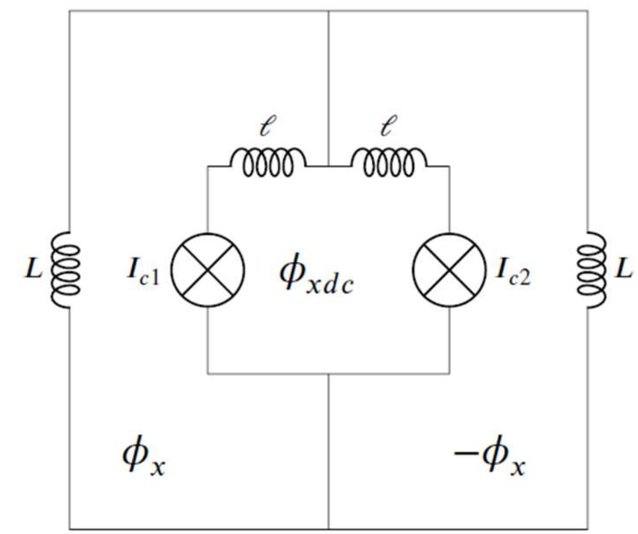
Gigahertz Sub-Landauer Momentum Computing

Work by Ray & Crutchfield, arxiv:2202.07122









Conclusion

The long-neglected *ballistic* mode of reversible computing has recently attracted renewed interest

Classic problems with chaotic instability are seemingly addressed via the asynchronous approach

Holds promise for achieving improved energy-delay products vs. adiabatic approaches

- Also, note that ballistic approaches are not viable in CMOS!
  - Unique advantage of superconductivity here.

Multiple US research groups in superconductor physics & engineering are making progress

We invite our international colleagues to join us in investigating this interesting line of research