Asynchronous Ballistic Reversible Computing using Superconducting Elements (Project #41)

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ACS BAA Portfolio Review
WebEx
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Contributors to the larger effort:

- Full group at Sandia:
  - Michael Frank (Nonconventional Computing)
  - Rupert Lewis (Quantum Phenomena)
  - Nancy Missert (Nanoscale Sciences)
    - Matt Wolak
  - David Henry (MESA Hetero-Integration)

- Thanks are also due to the following colleagues & external collaborators:
  - Erik DeBenedictis
  - Kevin Osborn (LPS/JQI)
    - Liuqi Yu
  - Steve Kaplan
  - Rudro Biswas (Purdue)
    - Dewan Woods
  - Karpur Shukla (CMU/Brown U.)
    - w. Prof. Jingming “Jimmy” Xu
  - David Guéry-Odelin (Toulouse U.)
  - FAMU-FSU College of Engineering:
    - Sastry Pamidi (ECE Chair)
    - Jerris Hooker (Instructor)
    - Fadi Matloob
      - Frank Allen
      - Oscar L. Corces
      - James Hardy
  - Others may be forthcoming...

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Outline of talk

- **Motivation:** Improving *dissipation-delay efficiency* in SCE
  - Appears limited in existing SCE logic families (as well as in CMOS)
  - Can we find a new SCE logic style that may give a path forward?

- **Approach:** Reversible computing without clocking overhead?
  - Adiabatic SCE logic families have dissipation/op $\propto 1/(transition\ time)$
    - Typical in *classical* adiabatic processes: *e.g.* resistance, friction, viscosity
    - However, *quantum* adiabatic processes can do better than this!
      - Exponential adiabaticity of Landau-Zener transitions in scattering proc.
  - Can elastic scattering of fluxons do *ballistic* reversible computing?
    - Use *Asynchronous Ballistic Reversible Computing* model of computation

- **ACI/ACS-funded project at Sandia:**
  - Review of progress to date: LJJ interconnects, RM cell, test chip
  - Project plan looking forwards:
    - Continued technology development (more circuits / experimental tests)
      - Also investigating whether theoretical methods of *superadiabaticity* / *shortcuts to adiabaticity* (STA) might be applied in fluxon-based systems
Three main technical thrusts:
- Theory, Modeling, Applications
  - PI – M. Frank
- Devices, Circuits & Simulation
  - Co-PI – R. Lewis
- Fabrication, Measurement
  - Key Personnel: N. Missert

University subawards:
- Design Tools (FAMU/FSU)
  - Matloob, Allen, Corces, Hardy
- Fundamental Physics (Brown)
  - K. Shukla w. J. Xu
- Circuit Analysis (Purdue)
  - R. Biswas & D. Woods

One year base period and two one-year option periods
Dissipation-delay Efficiency (DdE)

- A key motivating Figure of Merit (FOM) in the present study.
- For a single *primitive* transition of the digital state of a system between two distinct informational states, consider:
  - The energy dissipation $D$ incurred by that transition process.
    - Relates to real-world costs associated with supply of energy and cooling.
  - The delay $d$, defined as the time interval from start to end of process.
    - Relates to costs associated with achieving a given level of parallel performance.
- Then define the *dissipation-delay product* $DdP = D \cdot d$.
  - Note that since $D$ refers specifically to energy *dissipation*, not to energy *invested* in the signal, in reversible processes, it is *not subject to the “quantum speed limit”* (QSL) lower bound of $\sim h!$ (E.g. Margolus-Levitin)
    - No *fundamental* lower bound to $DdP$ is yet known!
      - In fact, it would be identically zero for any perfectly-known unitary time-evolution.
  - Of even more general interest than $DdP$ per se is dissipation as a function of delay, $D(d)$, considered over a range of practical (tolerable) delay values...
    - We’d like to extend the *pareto frontier* of this function within the useful range.
- *Dissipation-delay efficiency* (DdE) of a given computing technology just refers to the reciprocal of $DdP$, $\eta_{Dd} = (Dd)^{-1}$. 
Existing Dissipation-Delay Relations

One CMOS logic gate

RQFP = Reversible Quantum Flux Parametron (Yokohama U.)

Energy ×4, Delay ×3
For full adder function

Source: IRDS ‘17
More Moore chapter

Data from
T. Yamae,
ASC ‘18

$kT @ T = 300 K$

$kT @ T = 4 K$
Exponential Scaling of Efficiency?

- Can we do *better than linear* scaling of dissipation with speed? → **YES!**
  - Some observations from Pidaparthi & Lent, 2018 →
- Landau-Zener ’32 (!) formula for quantum transitions in *e.g.* atomic scattering problems with a missed level crossing...
  - Shows that the probability of exciting the (dissipative) high-energy state scales down *exponentially* as a function of speed...
    - This *exponential* adiabaticity is a commonly-seen feature of many quantum systems!
  - .:. Dissipation-delay *product* has **no lower bound** for quantum adiabatic transitions!
    - Also... With *superadiabaticity* a.k.a. *shortcuts to adiabaticity*, we can do even better!
      - Approach 0 diabaticity even @ very *fast* speeds!
        - More on this later...

\[ P_D = e^{-2\pi \Gamma} \]
Can we envision reversible computing as a *deterministic* elastic scattering process?

Historical origin of this concept:
- Fredkin & Toffoli’s *Billiard 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, 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 resynchronization incurs an inevitable energy cost.

Can we come up with a new ballistic model that avoids these problems?
Asynchronous Ballistic Reversible Computing in Superconducting Electronics (LDRD at Sandia)

- **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)
  - *E.g.*, positions/velocities of ballistically-propagating pulses

- **Core insight:** In principle, we can greatly reduce or eliminate this tendency towards dynamical chaos...
  - *We can do this by avoiding* any direct interaction between continuous DOFs of different ballistically-propagating signals

- 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 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

- 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 project:** Demonstrate ABRC principles in an implementation based on fluxon dynamics in SCE
WRSPICE simulations of discrete LJJ

- Preliminary effort completed in FY18
  - ASC (Sep. ‘18) [10.1109/TASC.2019.2904962](https://doi.org/10.1109/TASC.2019.2904962)
- Modeled buildable test structures in Xic
- Confirmed ballistic fluxon propagation
  - Confirmed predicted dLJJ line impedance of 16 Ω
Another FY18 task was: Characterize the simplest nontrivial ABRC device functionalities, given a few simple design constraints applying to an SCE-based implementation, such as:

- Bits encoded in fluxon polarity;
- Bounded planar circuit conserving flux;
- Physical symmetry.

Determined through theoretical analysis that the simplest such function is the following 

1-Bit, 1-Port Reversible Memory Cell (RM):

- Due to its simplicity, this is the preferred target for our detailed circuit design efforts looking forwards...

**RM Transition Table**

<table>
<thead>
<tr>
<th>Input Syndrome</th>
<th>Output Syndrome</th>
</tr>
</thead>
<tbody>
<tr>
<td>+1(+1)</td>
<td>(+1)+1</td>
</tr>
<tr>
<td>+1(−1)</td>
<td>(+1)−1</td>
</tr>
<tr>
<td>−1(+1)</td>
<td>(−1)+1</td>
</tr>
<tr>
<td>−1(−1)</td>
<td>(−1)−1</td>
</tr>
</tbody>
</table>

Some planar, unbiased, reactive SCE circuit (to be designed) 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)
- *Elastic scattering* type interaction: Input fluxon kinetic energy is (nearly) preserved in output fluxon
Erik DeBenedictis: “Try just strapping a JJ across that loop.”
  - This actually works!

JJ sized to = about 5 LJJ unit cells (~1/2 pulse width)
  - I first tried it twice as large, & fluxons annihilated instead...
    - 😐 “If a 15uA JJ rotates by $2\pi$, maybe $\frac{1}{2}$ that will rotate by $4\pi$”

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

WRspice simulations with +/-1 fluxon initially in the loop
  - Uses \texttt{ic} parameter, & \texttt{uic} option to \texttt{.tran} command
    - Produces initial ringing due to overly-constricted initial flux
      - Can damp w. small shunt $G$
WRspice simulation results

Polarity mismatch $\rightarrow$ Exchange

Polarity match $\rightarrow$ Reflect (=Exchange)

Loop current $-6\mu A$  
Junction current ↓  
Junction phase 0  
2$\Phi_0$ flux crossing junction

Loop current $+6\mu A$  
Junction current ↑  
Junction phase 4$\pi$

Loop current $+6\mu A$  
Junction current ↑  
Junction phase 0  
Zero net flux transfer

100-segment discrete Long Josephson Junction (dLJJ) line
Resettable version of RM cell

- For testing—apply current pulse of appropriate sign to flush the stored flux (the pulse here flushes out positive flux)
  - To flush either polarity → Just do both (±) resets in succession
**SPICE simulation of RM cell reset**

- Simulates as expected (one-polarity reset shown)
  - Reset of an already-flushed cell is a no-op

(Note no effect from 2nd reset)
Sketch of SQUID-based test setup

LJJ has $I_cL \ll \Phi_0$
RM has $I_cL = \Phi_0$

LJJ will contain many segments, only 3 are drawn

RM cell
Test Circuit Layout

- Circuit elements were rescaled for operation @ 4K (10 × larger $I_c$ values)
- Complete test circuit layouts were generated for SeeQC’s 4-layer Nb process
  - Low $J_c = 1 \, \mu A/\mu m^2$ increases layout dimensions, reduces manufacturing variation
- A 5 × 5 mm die with 4 test circuits was taped out on Feb. 17th
Some Next Steps re: RM Cell

- Detailed design & empirical testing of a physical prototype.
  - Experimentally measure the fabricated circuits in our lab.
- Need to understand better, at a theoretical level, the engineering requirements for such circuits to work properly.
  - And, can we generalize this understanding to more complex cases?
    - Goal: Design circuits for a wide variety of other ABRC functions.
- Carry out further elaborations of design to fine-tune dynamic response for high-fidelity preservation of pulse shape.
  - Should be able to use 3D physics modeling, solve inverse problem to craft a very high-quality custom layout (similar to metamaterials).
- Investigate applications, *e.g.*:
  - Can this be extended to become the basis for a dense memory fabric?
    - Develop row/column interface logic
    - Optimize the cell design for more compact area
      - Try smaller loop inductance, larger $I_c$ in I/O junction
  - Can this cell have utility in quantum computer control circuits?
    - See next slide
RM Cells for Qubit Control?

Idea by Rupert Lewis

RM cells can be reconfigured with nearly zero energy dissipation near the qubit!

Note: Entire structure scales well to a low-$J_c$ process for decreased fluxon energy and even lower energy dissipation, while maintaining good noise immunity at QC temperatures (~10s of mK)
Kevin Osborn (w. W. Wustmann & L. Yu) at LPS have recently also begun exploring stateful gates in the ABRC family...

- This one is functionally similar to the RM cell, except the output comes out a different port
- Function was verified in detailed simulations →
  - Error margins are ≥30%
  - Peak efficiency ≥90%

(Related to our 1-bit gates)

Inductor loop “precharged” with 1 SFQ. Ls allows storage of one SFQ, at most

“Forward-scattering [reversible] shift register cell”
Due to the novelty of our new logic style, the principles to design much improved/more complex ABRC circuits aren’t obvious…

**Solution:** Automate our circuit-discovery methodology!

Started developing a new tool, named **SCIT**

*Superconducting Circuit Innovation Tool*

Outline of the SCIT processing flow:

1. Define circuit design requirements
2. Enumerate possible circuit topologies
   - In order of increasing complexity
3. Delegate topologies to MPC nodes
4. Sweep over device parameter space
5. Generate a netlist for each test design
6. Simulate netlist locally (in e.g. WRspice)
7. Interpret & summarize resulting traces
8. Filter for results with desired properties
9. Facilitate visualization of candidate designs
Multi-year Senior Design projects in ECE Department, FAMU-FSU College of Engineering

- Department chair Sastry Pamidi and course instructor Jerris Hooker have some superconductivity expertise
  - College has historical ties with adjacent Mag Lab (NHMFL)
- This year’s students:
  - Fadi Matloob, Frank Allen, Oscar Corces, James Hardy

Present status:
- Some software components already functional
- Project temporarily stalled due to university shutdown
  - Project file server not accessible 😞
Superadiabaticity / Shortcuts to Adiabaticity (STA)

- A line of fundamental physics research showing that we can theoretically attain or approach 0 diabaticity (dissipation) even in evolutions occurring at fast, constant speeds.
  - This relates to my more general point from earlier about the fundamental dissipationlessness of known unitary evolutions.

- Some (at least theoretical) applications of this so far:
  - *Fast* Carnot-efficient heat engines!
  - Fast general thermodynamic engines for manipulating the state of quantum systems (*e.g.* Maxwell’s Demon type setups).
  - Faster superconducting circuits for controlling quantum computers!

- Why not also investigate whether these methods can be used to achieve fast *classical* dissipationless reversible computing?
  - And whether this theory can translate to engineering practice...
Example Use of STA: Fast Dissipationless Transitions of a Quantum Dot System

- Credit: David Guéry-Odelin (U. Toulouse)
- Example system:
  - A quantum-dot system previously described by Lent for use in reversible logic, undergoing an (externally-driven) transition between two different Hamiltonians.
- Figures show occupancy of ground (top) & 1st excited eigenstate (bottom).
  - $t$ is the total time over which the transition takes place (adjustable)
  - $t_{\text{max}}$ is a somewhat arbitrary duration when the system is transitioned at certain designated “maximum speed” (at which dissipation is near maximum)
- If system later relaxes from an excited state → state energy will be dissipated.
  - But, we assume here that the relaxation time is large compared to the transition time itself.
- Both figures below show an example calculation at which transition speed = 1/5 maximum
  - But, the same method works in principle to achieve zero dissipation at any speed!

Normal quantum adiabatic process: Substantial excitation/dissipation

Using counterdiabatic protocol: Zero net excitation/dissipation
Open Problems in STA for RC

- Can any of the various STA protocols that theorists have described actually be implemented *practically*?
  - Need more exploration of engineering mechanisms for doing so.
  - What are the limits on these methods’ efficiency *in practice*, if any?
- Can the STA protocols be applied (in a complete way) to various specific examples of physical implementations of reversible computing?
  - In particular (for our project): Is there any way to apply them to fluxon dynamics, specifically in ABRC-type circuits?
    - Certain classical-quantum equivalences suggest yes!
      - See next slide
    - Could an appropriate counterdiabatic Hamiltonian be introduced spatially, through appropriate tailoring of the structure at which the fluxon dynamics occurs?
- However, best way to proceed is still very unclear!
  - This is a wide-open research area...
Shortcuts to Fluxon Adiabaticity?

Work in progress with Karpur Shukla (CMU / Flame U. / Brown U.)

- Jarzynski ‘13 [1] discusses *dissipationless classical driving*, which can be viewed as an example of a classical analogue to quantum shortcuts to adiabaticity (STA)
  - Prescribes theoretical modifications to driving Hamiltonian
- Okuyama & Takahashi ‘17 ([10.7566/JPSJ.86.043002](10.7566/JPSJ.86.043002)) builds a more complete theory of classical STA on this foundation...
  - *Korteweg-de Vries (KdV) hierarchy* characterizes conserved quantities
    - Gesztesy & Holden ‘97 [2] show how to modify the KdV hierarchy as needed to model the sine-Gordon equation—describes fluxons in LJJ!
- Takahashi ‘19 ([10.7566/JPSJ.88.061002](10.7566/JPSJ.88.061002)) goes on to discuss methods for *Hamiltonian engineering* in the context of adiabatic QC...
  - Can apply to engineering classical reversible transformations also?
    - Needs more study...

Conclusion

- Some path to further **increase dissipation-delay efficiency** of superconducting circuits over the long term is needed.
  - **No fundamental limit** on this quantity is yet known!
- Inspired by **collision-based computing**, we have simulated the first concrete working example of an SCE circuit implementing one of the reversible functions in the new ABRC model of computation.
  - This is a **reversible memory (RM)** cell functionality requiring just 1 JJ.
  - Some of the key **next steps** for the RM cell development include:
    - **Empirically test** our first test chips once we get them back.
    - **Design additional test chips** for purposes of measuring energy dissipation.
    - **Identify additional functions** in the ABRC model that may be amenable to producing similarly straightforward implementations.
    - **Finish implementing circuit search tool** (SCIT) for more rapid discovery of circuits for more complex ABRC functionalities.
- In the bigger picture, there is a significant need to begin investigating new quantum (or quantum-inspired) techniques for reducing dissipation in reversible computational processes.
  - **Shortcuts-to-adiabaticity** (STA) is just one example of such an approach
  - **Other ideas:** Harness topological invariants, quantum Zeno effects, etc.
- Many possible paths still remain to be explored for **continuing to improve dissipation-delay efficiency** far into the future.