Reversible Computing as the Sustainable Path Forward for General Digital Computing

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Abstract (bullet-point version)

All conventional (i.e., non-reversible) digital computing is approaching a hard thermodynamic limit on its energy efficiency (and therefore also cost-efficiency, assuming only a cost floor for energy).

◦ Industry is already struggling to improve performance metrics; semiconductor roadmap ends in ~10 yrs.
◦ Digital computing (in the conventional paradigm) is faced with **permanent technological stagnation**.

**BUT! There is a solution** (but only one!) that can allow us to sustain continuing improvements in energy & cost efficiency for digital technology far into the future: **Reversible Computing (RC)**.

◦ Refers to computing in a way that **recovers signal energies** and reuses them for multiple digital operations.
  ◦ This is not a trivial change! It requires re-design and re-optimization of devices, circuits, architectures at multiple levels.
◦ It is **distinct** from quantum computing, although it may also leverage quantum phenomena & principles.
  ◦ Focus of RC is on achieving **far greater energy efficiency and practical performance** for **ALL** digital computing, rather than quantum speedups on relatively few specialized applications.
  ◦ Arguably, RC’s eventual practical & economic impact can therefore be **much broader and greater** than that of QC.
    ◦ By the end of the century, reversible computing could dominate the rest of the computing market by many orders of magnitude.

◦ Reversible computing needs to be **front and center** in all high-level discussions about the long-term future of computing technology (or at least on a par with the more “fashionable” topics of neuro/quantum).
  ◦ Far more attention should be being paid to it, as a viable technology development path.
  ◦ A large-scale initiative is needed to help push this technology forward.
Outline of Talk

Reversible Computing as The Sustainable Path Forward for General Digital Computing

I. Introduction: Motivation & History.
- Landauer’s Principle and Early Developments
- The Fundamental Economics of Computing Cost Efficiency
- The Dissipation-Delay Efficiency Metric & Trends

II. Reversible Computing with Adiabatic CMOS.
- Basic Principles of Adiabatic Switching.
- Fully Adiabatic CMOS with 2LAL
- Fully Static, Fully Adiabatic CMOS with S2LAL

III. Reversible Superconducting Technologies.
- Adiabatic Reversible Quantum Flux Parametron logic.

IV. Fundamental Physical Limits of Reversible Computing.
- Exponential Adiabaticity and Asymptotic Scaling.

V. Future Work and Conclusion.
Section I. Motivation & History

Reversible Computing as The Sustainable Path Forward for General Digital Computing
Landauer’s Principle (1961):
- Elementary statistical physics and information theory together imply that there is a fundamental upper bound on energy efficiency for the conventional (non-reversible) computing paradigm.
- **Oblivious** erasure of known/correlated information implies dissipation of \( E_{\text{diss}} \geq k_B T \ln 2 \) energy to the environment for each bit's worth of known information that is lost.
- \( k_B \) is Boltzmann's constant \( \approx 1.38 \times 10^{-23} \) J/K = the natural logarithmic unit of entropy.
- **NOTE:** \( T \) is the temperature of the thermal environment into which the waste heat ends up getting ejected.
- \( \therefore \) Simply lowering \( T \) **locally** cannot help **directly** to lower system-level \( E_{\text{diss}} \) if the external environment temperature is fixed.

Reversible Computing (RC) provides a (theoretical, and eventually also practical!) solution:
- RC means computing **without** oblivious erasure of known or correlated information.
- In principle, energy dissipation per useful operation can be made **arbitrarily small** (can approach zero as technology improves).
- \( \therefore \) Energy efficiency (operations per Joule) can theoretically approach **infinity** (or at least, no limits to this are yet known).
- This includes implications for avoiding differential power analysis (DPA) and related side-channel attacks.

Some early history of the reversible computing field:
- RC was first shown **theoretically** coherent by Bennett, 1973 (doi:10.1147/rd.176.0525).
- First **engineering** implementation proposed by Likharev, 1977 (doi:10.1109/TMAG.1977.1059351).

The time is ripe for a resurgence!
- I believe there is an opportunity right now to demonstrate some real breakthroughs.
Semiconductor Roadmap is Ending…

Thermal noise on gate electrodes of minimum-width segments of FET gates leads to significant channel PES fluctuations if $E_R \lesssim 1-2$ eV!
- This increases leakage, impairs practical device performance
- Thus, roadmap has minimum gate energy asymptoting to $\sim 2$ eV

Further, real logic circuits incur many compounding overhead factors multiplying this raw transistor-level limit:
- Transistor width $10-20\times$ minimum width for fastest logic.
- Parasitic (junction, etc.) transistor capacitances ($\sim 2\times$).
- Multiple ($\sim 2$) transistors fed by each input to a given logic gate.
- Fan-out of each gate to a few ($\sim 3$) downstream logic gates.
- Parasitic wire capacitance ($\sim 2\times$).

Due to all these overhead factors, the energy of each logic bit in real logic circuits is necessarily many times larger than the minimum-width gate energy!
- $375-600\times$ (!) larger in ITRS’15.
- $\therefore$ Practical bit energy for irreversible CMOS logic asymptotes to $\sim 1$ keV!

Practical, real-world logic circuit designs can’t just magically cross this $\sim 500\times$ architectural gap!
- $\therefore$ Thermodynamic limits imply much larger practical limits!
- The end is near!

Only reversible computing can take us from $\sim 1$ keV at the end of the CMOS roadmap, all the way down to $\ll kT$. 
Why Reversible Computing Wins Despite Its Overheads!

Bumper-sticker slogan: “Running Faster by Running Slower!” (Wait, what?) More precisely:
- Reversible technology is so energy-efficient that we can overcome its overheads (including longer transition times!) by using much greater parallelism to increase overall performance within system power constraints.
- This is borne out by a detailed economic/systems-engineering analysis.

**Bottom line:** The computational performance per unit budgetary cost on parallelizable computing workloads can become as large as desired, given only that both terms in this expression for total cost per operation $C_{\text{op}}$ can be made sufficiently small:

$$C_{\text{op}} = c_E \cdot E_{\text{diss,op}} + c_M (s_{\text{elem}} \cdot t_{\text{delay}}).$$

where:
- $c_E$ is the operating cost $C_{\text{oper}}$ attributable to supplying power/cooling, divided by energy delivered.
- $E_{\text{diss,op}}$ is the system energy dissipation, divided by number of operations performed.
- $c_M$ is the total cost $C_{\text{mfg}}$ for system manufacturing & installation, divided by the number $n_{\text{elem}}$ and physical size $s_{\text{elem}}$ (in appropriate units) of individual computing elements, & the system’s total useful lifetime $t_{\text{life}}$.
- $t_{\text{delay}}$ is the average time delay between instances of re-use of each individual computing element.

Two key observations:
- The cost per operation of all conventional computing approaches a hard floor due to Landauer.
- Assuming only that the economic cost of operation per Joule delivered cannot become arbitrarily small.
- But, there is no clear barrier to making the manufacturing cost coefficient $c_M$ ever smaller as manufacturing processes are refined (and/or the deployed lifetime of the system increases).

$\therefore$ Nothing prevents system-level cost efficiency of reversible machines from becoming arbitrarily larger than conventional ones, even if we have to scale $t_{\text{delay}}$ and/or $s_{\text{elem}}$ up as we scale $E_{\text{diss,op}}$ down!
What is dissipation-delay efficiency, and why is it important?

Typically, the total cost $\$_{\text{tot}} = \$_{E} + \$_{M}$ to perform a computation is minimized when energy-related costs $\$_{E}$ and manufacturing-related costs $\$_{M}$ are roughly on the same order.

- Because, there are diminishing returns from individually reducing either one of these two cost components far below the other one.
- And, doing so actually makes the total larger, if the other cost component gets increased as a result.

Can express total cost in terms of device parameters: $\$_{\text{tot}} = k_{E}E_{\text{diss}} + k_{M}t_{\text{del}}$

For any technology that permits tradeoffs between energy efficiency and serial performance, there will be some region of the energy-delay curve where the tangent line (on a log-log chart) has slope $-1$.

- In this region, the energy-delay product is roughly constant.
- This is even true for voltage scaling in standard irreversible CMOS.
- But, fully adiabatic techniques can extend this scaling region over a much wider range.
- Different operating points in this linear scaling region will be suitable for applications with different cost coefficients $k_{E}, k_{M}$ that apply to energy vs. manufacturing cost.
- E.g., in spacecraft, the effective cost of energy vs. hardware is much greater than in grid-tied applications.

NOTE: If you can move to a new technology whose energy-delay frontier (curve) touches a min. energy-delay product line that is $N \times$ lower than before,

- Then it follows that total cost for some applications is reduced by at least $\sqrt{N} \times$!
Existing Dissipation-Delay Products (DdP) — Non-reversible Semiconductor Circuits

Conventional (non-reversible) CMOS Technology:

- Recent roadmaps (e.g., IRDS ‘17) show Dissipation-delay Product (DdP) decreasing by only $<\sim10\times$ from now to the end of the roadmap (~2033).
  - Note the typical dissipation (per logic bit) at end-of-roadmap is projected to be $\sim0.8 \text{ fJ} = 800 \text{ aJ} = \sim5,000 \text{ eV}$.
  - Optimistically, let’s suppose that ways might be found to lower dissipation by an additional $10\times$ beyond even that point.
    - That still puts us at $80 \text{ aJ} = \sim500 \text{ eV}$ per bit.
  - We need at least $\sim1 \text{ eV} \approx 40 \, kT$ electrostatic energy at a minimum-sized transistor gate to maintain reasonably low leakage despite thermal noise,
    - And, typical structural overhead factors compounding this within fast random logic circuits are roughly $500\times$,
    - so, $\sim500 \text{ eV}$ is indeed probably about the practical limit.
      - At least, this is a reasonable order-of-magnitude estimate.
Section II. Reversible Computing with Adiabatic CMOS

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Adiabatic Charging via MOSFETs

A simple voltage ramp can *approximate* an ideal constant-current source.

- Note that the load gets charged up *conditionally*, if the MOSFET is turned on (gate voltage $V_g \gtrsim V + V_t$) during ramp.
- $V_t$ is the transistor's threshold, typically $< \frac{1}{2}$ volt

Can discharge the load later using a similar ramp.

- Either through the same path, or a different path.

\[
\begin{align*}
t \gg RC & \Rightarrow E_{\text{diss}} \rightarrow CV^2 \frac{RC}{t} \\
t \ll RC & \Rightarrow E_{\text{diss}} \rightarrow \frac{1}{2} CV^2
\end{align*}
\]

The (ideal) operation of this circuit approaches *physical reversibility* ($E_{\text{diss}} \rightarrow 0$) in the limit $t \rightarrow \infty$, but *only* if a certain *precondition* on the initial state is met (namely, $V_g \gtrsim V_{\text{max}} + V_t$).

- How does the possible physical reversibility of this circuit relate to its *computational* function, and to some *appropriate* concept of logical reversibility?

  - Traditional (Landauer/Fredkin/Toffoli) reversible computing theory does *not* adequately address this question, so, we need a more powerful theory!
  - The theory of *Generalized Reversible Computing* (GRC) meets this need.

See arxiv:1806.10183 for the full GRC model.
Basic Requirements for Fully Adiabatic Operation

No diodes in charging paths!
- All diodes have a built-in voltage drop for fundamental thermodynamic reasons.

Operate all switches (e.g., FETs) with a “dry-switching” discipline:
- Never turn on (close) a switch when there is a significant voltage difference $\Delta V \neq 0$ between its terminals.
  - Leads to a sudden, non-adiabatic flow of current.
  - More generally: No rapid voltage changes.
- Never turn off (open) a switch when there is a significant current flow $I \neq 0$ through the switch.
  - Leads to non-adiabatic losses as switch is (non-instantaneously) turning off.
    - Resistance through switch increases during turnoff $\rightarrow$ voltage drop increases $\rightarrow$ non-adiabatic loss across voltage drop.
    - Exception: If path has low inductance and there is an alternate path for the current.

Use quasi-trapezoidal driving waveforms (no steep edges; flat tops and bottoms).
- This is necessary to obey the other rules.

$$E_a = \xi_{tr} C_L V_{dd}^2 \frac{R C_L}{\tau_{tr}}$$
**Review of 2LAL**

2LAL is a simple variant of CRL, first described by M. Frank in lectures at the University of Florida in 2000.

- Four clock phases, each active for one tick and inactive for one tick.
- A simple (one-symbol) shift register structure is shown.
- Series/parallel combinations of transmission gates can be used to do logic (not shown here).
- 2LAL really only differs from CRL in terms of allowing more flexibility in how internal nodes are handled.

**Simulation results for 2LAL obtained at Sandia in 2020:**

- Energy dissipation per cycle per FET in shift register @50% activity factor at $f = 1$ MHz, $C_L = 10$ fF:
  - Spectre simulation of MESA 350 nm, $W = 800$ nm: $37 \text{ aJ} \approx 230 \text{ eV}$.
  - Spectre simulation of MESA 180 nm, $W = 480$ nm: $6.9 \text{ aJ} \approx 43 \text{ eV}$. ← Comparable to a data point for TSMC18 from 2004.
    - This beats end-of-roadmap standard CMOS substantially.

**Test chip taped out in Aug. 2020:**

- MESA 180 nm shuttle run.
- 2×2 mm die.
- 8-stage & 720-stage shift registers.
- Goal: Verify function & dissipation.
S2LAL Reversible Pipeline Structure

Paired forward and reverse stages:
- Forward stages activate to compute later signals from earlier ones.
- Reverse stages de-activate to de-compute earlier signals from later ones.

Every signal $S_i$ must stay active for (at least) 5 ticks:
- Provides sufficient time for the following sequence of steps:
  - (1) Activate forwards stage $F_{i+1}$, (2) Activate reverse stage $R_i$, (3) Handoff control of $S_i$ from $F_i$ to $R_i$, (4) Deactivate forwards stage $F_i$, (5) Deactivate reverse stage $R_{i-1}$.

Add 3 ticks for transitions & inactive handoff:
- Total cycle length = 8 ticks min.

Note control of each signal $S_i$ is handed off to forward stage $F_i$ on ticks $#i - 1$, and to reverse stage $R_i$ on ticks $#i + 3$.
- Signal $S_i$ goes valid on ticks $#i$ and invalid (inactive) on ticks $#i + 6$.

For general logic, functions must be invertible.
- Optimizing whole pipeline gets into reversible algorithm design: Considered out of scope for this particular paper.
Section III. Reversible Superconducting Technologies

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Adiabatic Reversible Computing in Superconducting Circuits

Work along this general line has roots that go all the way back to Likharev, 1977.

Most active group at present is Prof. Yoshikawa’s group at Yokohama National University in Japan.

Logic style called Reversible Quantum Flux Parametron (RQFP).

Shown at right is a 3-output reversible majority gate.

Full adder circuits have also been built and tested.

Simulations indicate that RQFP circuits can dissipate $< kT \ln 2$ even at $T = 4K$, at speeds on the order of 10 MHz.
Existing Dissipation-Delay Products (DdP)—Adiabatic Reversible Superconducting Circuits

Reversible adiabatic superconductor logic:
- State-of-the-art is the **RQFP** (Reversible Quantum Flux Parametron) technology from Yokohama National University in Japan.
- Chips were fabricated, function validated.
- Circuit simulations predict DdP is >1,000× lower than even end-of-roadmap CMOS.
- Dissipation extends far below the 300K Landauer limit (and even below the Landauer limit at 4K).
- DdP is still better than CMOS even after adjusting by a conservative factor for large-scale cooling overhead (1,000×).

**Question:** Could some other reversible technology do even better than this?
- We have a project at Sandia exploring one possible superconductor-based approach for this (more later)…
- But, what are the fundamental (technology-independent) limits, if any?
**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)
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…

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*
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
Section IV. Fundamental Physical Limits of Reversible Computing
This is a severely under-studied topic, but preliminary theoretical indications to date are that:

- For quantum-mechanical reversible devices that are well isolated from their thermal environment, there is a regime in which exponential adiabaticity (i.e., Landau-Zener scaling) can substantially suppress dissipation even at relatively high speeds (Pidaparthi & Lent ‘21)


- This result could have enormous practical implications for the economic competitiveness of reversible computing.

- At slow speeds, dissipation asymptotically converges to the classic adiabatic scaling (1/delay). (Earley ‘20)


- Implies that asymptotically, performance boost from RC scales up with $\sqrt{D}$ ($D = \text{depth/thickness}$)

This is a result that actually dates all the way back to Frank & Knight ’97:


- It appears likely that fundamental theoretical tools from the field of non-equilibrium quantum thermodynamics (NEQT) can be applied to make the above results more general and rigorous.


Can dissipation scale better than linearly with speed?

Some observations from Pidaparthi & Lent (2018) suggest Yes!

- Landau-Zener (1932) formula for quantum transitions in e.g. scattering processes with a missed level crossing…
- Probability of exciting the high-energy state (which then decays dissipatively) scales down exponentially as a function of speed…
- This scaling is commonly seen in many quantum systems!
- Thus, dissipation-delay *product* may have no lower bound for quantum adiabatic transitions—*if* this kind of scaling can actually be realized in practice.
- *I.e.*, in the context of a complete engineered system.
- **Question:** Will unmodeled details (e.g., in the driving system) fundamentally prevent this, or not?

\[ P_D = e^{-2\pi \Gamma} \]
FIG. 10. Dissipated energy of an open system as a function of switching speed for different dissipation time constants. The dashed line is the excess energy of an isolated system. Here, the environmental temperature $k_B T / \gamma = 0.5$. 

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Goals of this effort:

- Look for fundamental physical limits of reversible computing
  - E.g., minimum entropy production per operation as a function of delay, temperature, etc.
- Identify ways to harness exotic quantum phenomena if needed to saturate the limits

Steps completed so far:

- Identification of classical computational states with disjoint sets of orthonormal basis states in a (time-dependent, in general) protocomputational basis $\mathcal{B}$.
- Formalization of what it means for a unitary quantum evolution $U^t_s$ on a computational system $\mathcal{S}$ (physical computer) to implement a given classical (and possibly reversible and/or stochastic) computational operation $O^t_s$ between times $s$ and $t$.

Research strategy looking forward:

- Computational states correspond to decoherence-free subspace blocks of overall Hilbert space.
- Quantum Markov equation with multiple asymptotic states: admits subspace dynamics for open systems under Markov evolution.
  - Induces geometric tensor for manifold of asymptotic states.
    - Similar to quantum geometric tensor / Berry curvature for closed systems.
- Current work: use multiple asymptotic state framework to derive thermodynamic quantities…
  - Uncertainty relations, dissipation and dissipation-delay product.
Section IV. Future Work & Conclusion
Assessment of Architectural Implications

(Work with Tom Conte and Anirudh Jain, Georgia Tech)

Suppose the study of fundamental limits will be successful, and yield a better understanding of the limiting tradeoffs between dissipation, speed, etc.

- **Question:** What would be the **architectural** implications of attaining those limits?
- **Note:** We can begin exploring this question even before the main study yields results!

Research plan for Sandia/GT collaboration:

- **Sandia** defines a common **generic** model of abstract reversible device technologies (including adiabatic and/or asynchronous variants), characterized by key parameters and their scaling, e.g., $E_{diss}(t_d), P_{\text{leak}},$ etc.
- **Georgia Tech** designs a hierarchy of architectural components composed out of these generic reversible elements, leading towards a RISC style CPU architecture, including:
  - Multiplexers (32 bits wide, 2-to-1 and 4-to-1).
  - Comparators and Adders (32-bit-wide).
  - Integer Multipliers (32×32 bits, used for address arithmetic).
  - 32-bit ALU (Arithmetic-Logic Unit).
  - Canonical 5-stage pipelined RISC style processor including control unit.
- Meanwhile, **Sandia** supplies various special cases of the generic model reflecting interesting candidate (including hypothetical or preliminary) scaling relations emerging from main study.
  - **Georgia Tech** analyzes the effect of these particular model cases on the efficiency of architectural components
- **Georgia Tech** concludes by:
  - Conducting a study of the pareto optimal frontier of efficiency for partially-reversible architectures
Future Work

Some additional priority directions for future work in reversible computing technology include the following:

- **Adiabatic CMOS:**
  - Finish developing high-quality resonators, & integrate with fully adiabatic CMOS demonstration chips
  - Develop cell libraries and design tool enhancements to make adiabatic CMOS more accessible to designers
  - Design new FET geometries optimized for adiabatic operation at cryo temperatures
  - Develop commercializable adiabatic CMOS processors (both general- and special-purpose)

- **Reversible superconducting technologies:**
  - Continued development of the adiabatic reversible superconducting logic styles (AQFP/RQFP)
  - Continued development of the ballistic reversible superconducting logic styles (RFL/BARC)

- **Invent/develop novel device technologies for RC**
  - Harness topological invariants, quantum Zeno effects, other exotic phenomena?

- **Continue firming up fundamental physical limits of RC**
  - Derive a rigorous NEQT formulation of limits
Conclusion

Reversible computing will definitely be required in order for general digital computing to avoid hitting a plateau in gate-level energy efficiency, and beginning to stagnate in its development, within only the next decade or so…

- We had better begin working aggressively on it now for solutions to be ready in time!

Proof-of-concept implementations of reversible computing have already been constructed on top of both CMOS and superconducting technology platforms.

- Based on various concepts that have been under sporadic development since the 1970s.
- The technology is now ready for much more intensive practical development to start!

We have not even begun to approach the limits of what’s possible to achieve if reversible computing technologies are developed aggressively…

- There is a potential to gain, over time, vast economically beneficial improvements in system-level power-performance and cost-performance figures of merit for general digital computing applications!
- Potentially taking us orders of magnitude beyond any physically possible non-reversible technology!

There is an enormous opportunity here, that is just waiting for everyone to notice it.

- When the world finally realizes that reversible computing indeed offers a viable path forward that bypasses the roadblocks faced by conventional computing, it will be a watershed moment for the future of technology, and civilization in general.