Sandia National Laboratories

PRIORITY RESEARCH DIRECTION: **Physics & Engineering of Reversible Computing Hardware**

PRESENTED BY

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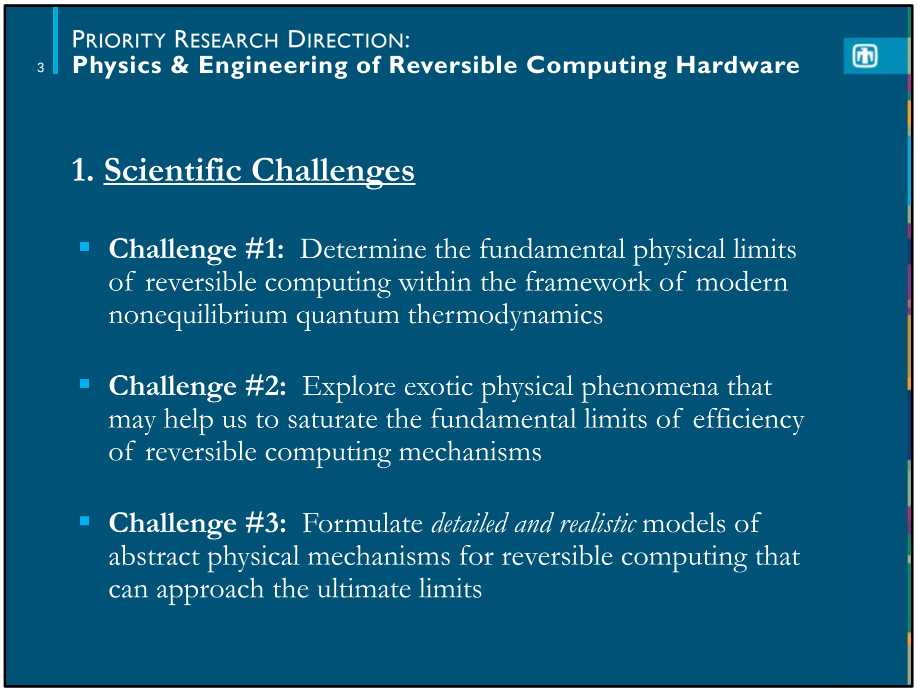
What is reversible computing?

- Landauer's principle sets a firm limit ($kT \ln 2$) on energy dissipation per bit (of *known* information) that is lost
- We can avoid Landauer's limit in deterministic digital computations *only* by computing without losing known bits
  - This is reversible computing
- The CS theory aspects of reversible computing are relatively well-developed (architectures, languages, algorithms)
- The *engineering* aspects of figuring out how to approach thermodynamically-reversible computing in high-performing physical computing mechanisms still need a lot of work
  - A number of implementation approaches are known
  - A greater variety of new engineering approaches need to be explored
  - Fundamental physical theory needs more development



1. Scientific Challenges

- **Challenge #1:** Determine the fundamental physical limits (if any) on reversible computing within the framework of modern nonequilibrium quantum thermodynamics
  - Consider the computing machine *including its power source and control system* as an open but *self-contained* physical system that interacts only *thermally* with an external heat bath.
    - ➢ Note this is very different from existing models of quantum computing, which typically invoke *external* control.
  - In such a setting, can we derive fundamental (technology-independent) limits on the energy-delay product for logically reversible operations, *e.g.*, as a function of the temperature of the thermal environment?
- **Challenge #2:** Explore the properties of fundamental physical phenomena that may help us to saturate the fundamental limits of efficiency of reversible computing mechanisms
  - **Example #1:** Dynamics of states encoding information in topological degrees of freedom—robust vs. fluctuations
  - **Example #2:** Utilization of the *quantum Zeno effect* (QZE) to enhance stability of dynamically-evolving pointer states
- **Challenge #3:** Formulate *detailed and realistic* models of abstract physical mechanisms for reversible computing that can approach the ultimate limits
  - A good such model will suggest approaches for the development of workable physical implementation technologies
  - Ideally, the model may even make it clear how to develop a *family* of technological implementations that asymptotically approaches the ultimate limits as the technology is further defined → A new scaling path!

2. Summary of Research Direction

- **Research Direction #1:** *Fundamental Physics of Reversible Computing*
  - Study the fundamental quantum thermodynamic limits of self-contained reversible computing machines, in an open-system, nonequilibrium framework within finite-temperature environments
  - Explore the potential utility of fundamental but little-explored physical phenomena (*e.g.*, topological solitons, quantum Zeno effect), for reducing dissipation in reversible computing mechanisms

- **Research Direction #2:** *Experimental Study of Reversible Technology*
  - Design and carry out careful experimental work in the laboratory to validate the fundamental theoretical results produced in R.D. #1, and provide the foundation for phenomenological and higher-level modeling in R.D. #3

- **Research Direction #3:** *Modeling for Reversible Computer Engineering*
  - Vertically-integrated modeling of reversible computing mechanisms, spanning the full range of levels from fundamental physics to multiprocessor system architecture
    - This would include the development of high-fidelity simulation capabilities
  - Goal of this work would be to build a well-justified case for investment in intensive R&D of the required technologies to implement reversible computing systems

3. Scientific Impact of Success

- **Impact #1:** *Advance the scientific understanding of the fundamental physics of computation*
  - Fundamental limits of reversible computing have never been studied in depth
- **Impact #2:** *Resolve the existing scientific controversy regarding the viability of reversible computing*
  - Rigorous physical theory, careful empirical work & sound technology modeling should help to exterminate any remaining skepticism
- **Impact #3:** *Long-term benefits to computational science*
  - Vastly greater system performance within power budget on *general* problems in scientific high-performance computing systems

4. Technological/Societal Impact of Success

- **Impact #1:** *Vastly greater efficiency of computing in general*
  - Note this contrasts with the more *special-purpose* benefits of other approaches
  - *No limit* is yet known to the efficiency gains achievable in the long term, but this is *only* true if reversible computing is used!
- **Impact #2:** *Reinvigorated US leadership in computing*
  - If this research direction proves successful, reversible computing will become *the* key technological foundation for *almost all* 21st–century computing
- **Impact #3:** *Incalculable gains for the entire global economy*
  - An increasing fraction of economic activity takes place in the computational realm — ∴ More computing efficiency translates to greater economic growth!

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