Letter

Extra cost of erasure due to quantum lifetime broadening

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The energy cost of erasing a bit of information was fundamentally lower bounded by Landauer, in terms of the temperature of its environment, $W \geqslant k_B T \ln 2$. Energy consumption and heat generation in computers is now a pressing issue, but real electronic devices operate out of equilibrium and are subject to other noise sources besides temperature. Considering a quantum dot charge bit as a concrete model, we here derive a tighter bound, rigorously quantifying the dissipative impact of lifetime broadening and potential difference, in terms of a few experimentally measurable parameters. In practical contexts, these additional contributions may significantly outweigh the cost due to temperature alone. The results shed light not only on theoretical limits of erasure but also on constraints in realistic devices.

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Introduction. The well-known fundamental limit on the energy consumption of information processing devices is Landauer's bound, which holds that the process of erasing a bit of information must dissipate at least $k_B T \ln 2$ of heat, where T is the temperature of the thermal environment [1]. As a keystone of the connection between thermodynamics and information theory, the foundational status of the bound has long been discussed [2,3]. Now, basic limits on energy dissipation are a pressing practical problem: Information technology consumes around 5% of the global electricity supply [4], and thermal management is a primary bottleneck for integrated circuit performance [5]. Part of the solution must come from optimizing the physical implementation of basic logic operations. As current complementary metal-oxide semiconductor (CMOS) transistor switching- energies are in the hundreds of $k_B T$ [6], improvement will require analysis and mitigation of the factors which prevent the Landauer bound from being approached in real-world conditions.

Progress towards this end has included proof-of-concept experimental demonstrations of erasure at $k_B T$-scale energy costs (more recently in solid state electronics) [7–13]. Meanwhile, theoretical advances have accounted for constraints beyond temperature [14], including the effects of finite-speed driving, finite-sized reservoirs, strong coupling, quantum coherence, and limited control complexity [15–20], leading to proposed optimizations using techniques from thermodynamic geometry [21–26]. However, important considerations have been overlooked: In particular, electronic components almost never interact with a single homogeneous thermal environment.

In this Letter, we analyze the thermodynamics of erasure in a quantum dot charge bit, which exchanges electrons with two electrodes with different temperatures and chemical potentials. Quantum dots represent the limit of miniaturization for devices with a source, gate, and drain electrode, and they are regarded as a promising platform for low-energy information processing [27–29]. By explicitly considering optimal erasure protocols, we identify and bound the scale of three inherent sources of energy dissipation. In addition to recovering the Landauer bound, we find independent contributions to the energy cost resulting from lifetime broadening of the dot's energy level, and source-drain potential difference. With reference to existing experimental devices [30,31], we find that these contributions can outweigh temperature-related dissipation in realistic regimes of operation, sometimes to the extent that Landauer's bound is practically irrelevant. Finally, we discuss the extent to which these energy costs might be mitigated, the generalizability of the results to other device types, and the theoretical significance of the role of lifetime broadening as a quantum source of noise.

Model device. We consider the charge bit device depicted in Fig. 1, consisting of a single-level quantum dot which exchanges electrons via tunneling with a source and drain electrode. The probability p that the dot contains an electron varies as a function of its energy level μ, which in turn is

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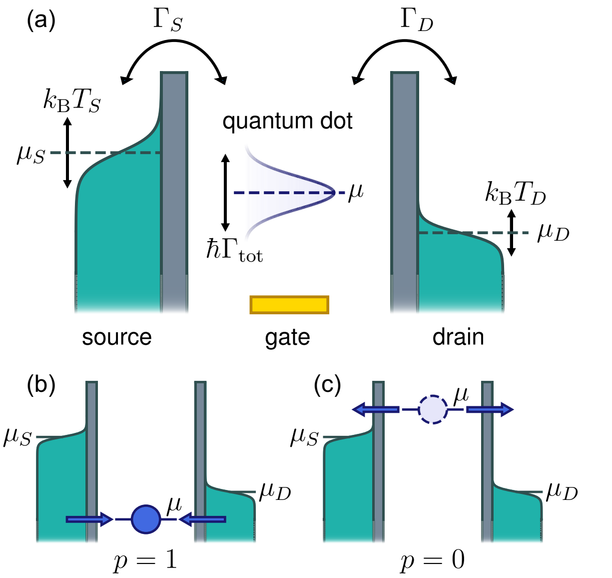

FIG. 1. (a) Schematic energy-level diagram of a quantum dot charge bit device. The dot exchanges electrons with a source and drain electrode via quantum tunneling, with characteristic rates Γ_S and Γ_D, respectively. Electrons in the source and drain are described by the Fermi-Dirac distribution with chemical potentials μ_S, μ_D, and temperatures T_S, T_D, respectively. A bit of information is encoded in the electronic occupation p of a single level of the quantum dot at energy μ, which is subject to lifetime broadening with scale $\sim\hbar\Gamma_{\rm tot}$. The occupation of the dot may be manipulated by externally varying μ via the electrostatic field from a gate electrode. (b) By lowering μ below μ_D, it can be ensured that the state is occupied, representing the digit 1. (c) If μ is raised above μ_S, electrons tunnel out of the dot leaving an empty state, representing the digit 0.

externally controlled by the electrostatic field from a gate electrode. The presence or absence of an electron in the dot may be taken to represent a 0 or 1 digit, encoding a bit of information. In this context, erasure means a transformation from the state of maximum ignorance ($p = \frac{1}{2}$) to certainty about the occupation of the dot, which can mean either $p = 0$ or $p = 1$ (reset to the logical zero or one state, respectively).

The work cost of erasure depends on the occupation distribution $p(\mu)$, which we model using a rate equation [see Supplemental Material (SM) [32]]. We assume that the dot exchanges electrons with the source and drain at fixed rates $\Gamma_{S,D}$, and that the electron reservoirs are described by the Fermi-Dirac distributions $f_{S,D}(\varepsilon)$ with respective temperatures $T_{S,D}$ and chemical potentials $\mu_S \geqslant \mu_D$. If lifetime broadening is neglected, the steady-state occupation of the dot is described by a convex combination of the source and drain Fermi-Dirac distributions, weighted by the tunneling ratios $\gamma_{S,D} = \frac{\Gamma_{S,D}}{\Gamma_S+\Gamma_D}$ [32,33]:

$$p_0(\mu) = \gamma_S f_S(\mu) + \gamma_D f_D(\mu). \tag{1}$$

However, at higher tunneling rates, the stronger coupling to the leads allows new transitions of electrons between the dot and the reservoirs. This results in an effective broadening of the available electronic states in the leads, which is commonly taken to have Lorentzian or Gaussian form, centered on μ and with characteristic width $\hbar\Gamma_{\rm tot}$, where $\Gamma_{\rm tot} = \Gamma_S + \Gamma_D$

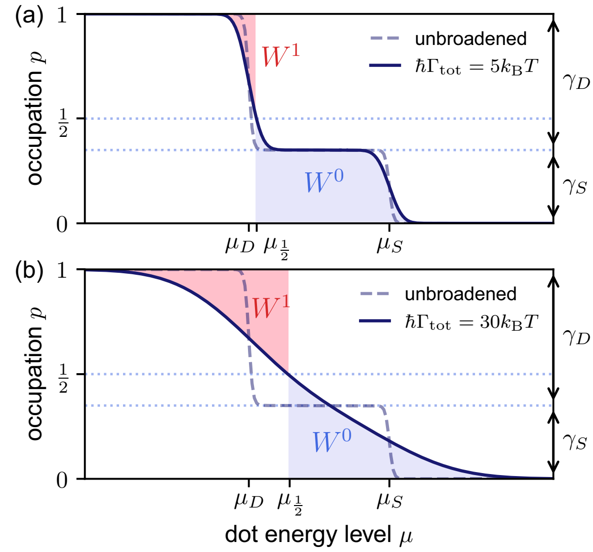

FIG. 2. Average occupation p plotted against energy level μ for a quantum dot in simultaneous contact with two electron reservoirs. The occupation is described by a weighted sum of the reservoirs' Fermi-Dirac distributions (dashed curve, both panels), which is smoothed due to lifetime broadening with scale $\hbar\Gamma_{\rm tot}$. Starting at $p = \frac{1}{2}$, the minimum work required to prepare the $p = 0$ state is represented by the blue shaded area W^0, and the cost of preparing $p = 1$ is represented by the red area W^1. Both processes represent erasure of a bit of information. In (a), the source-drain chemical potential difference $(\mu_S - \mu_D)$ is considerably larger than either the thermal $(k_B T)$ or lifetime broadening $(\hbar\Gamma_{\rm tot})$ energy scales, and therefore the average work cost of erasure $\overline{W} = \frac{1}{2}(W^0+W^1)$ is approximately $\frac{1}{2}\gamma_S(\mu_S - \mu_D)$, i.e., bias- dominated. In (b), lifetime broadening is comparable to the bias, and contributes significantly to $\overline{W}$. In both panels, the temperatures $T_S = T_D = T$, the bias $\mu_S - \mu_D = 36k_T$, and the tunneling ratios $\gamma_S = 0.35$, $\gamma_D = 0.65$. Lifetime broadening is taken to have Gaussian form with standard deviation $\hbar\Gamma_{\rm tot}$.

[34,35]. The overall occupation p (plotted in Fig. 2) is then given by the convolution[1] of the broadening distribution g with the unbroadened occupation p_0 from Eq. (1):

$$p(\mu) = (g \star p_0)(\mu) = \int_{-\infty}^{\infty} g(\varepsilon - \mu) p_0(\varepsilon) d\varepsilon. \tag{2}$$

Optimal erasure protocols. The quantum dot's occupation can be manipulated by externally varying its energy level μ via the gate electrode. The rate of work done on the dot is defined by $\dot{W} = p\,\dot{\mu}$ [36]. Let $\mu_{\frac{1}{2}}$ denote the value of μ such that $p(\mu_{\frac{1}{2}}) = \frac{1}{2}$. We here outline a thermodynamically reversible protocol for erasure to logical zero. Starting at $p = \frac{1}{2}$, the energy level μ is quasistatically[2] raised from $\mu_{\frac{1}{2}}$ towards $+\infty$ such that the dot's occupation vanishes. The level is then reset to $\mu_{\frac{1}{2}}$ much faster than the dot's equilibration timescale, such that the final occupation remains at $p = 0$. The overall work

[1]Strictly speaking, this is a *cross-correlation*, which is equivalent to a convolution when g is symmetric about μ.

[2]i.e., over a timescale much longer than $\Gamma_{\rm tot}^{-1}$.

done on the dot in this process is $W^0 = \int_{\mu_{\frac{1}{2}}}^{\infty} p(\mu) d\mu$. Erasure to "one" proceeds similarly. The energy level is slowly lowered from $\mu_{\frac{1}{2}}$ towards $-\infty$, before being quickly raised back to $\mu_{\frac{1}{2}}$, preserving the occupation $p = 1$. The work cost in this case is $W^1 = \int_{-\infty}^{\mu_{\frac{1}{2}}} [1 - p(\mu)] d\mu$. For more details, see SM [32].

Aside from exceptionally symmetric cases[3], W^0 and W^1 differ from one another (plotted as shaded areas in Fig. 2). In the context of information processing, ones are required just as frequently as zeros for efficient coding [37]. A fair measure of the cost of state reset is the average, $\overline{W} = \frac{1}{2}(W_0 + W_1)$, which may be written as [32]

$$\overline{W} = \frac{1}{2} \int_{-\infty}^{\infty} |\mu - \mu_{\frac{1}{2}}| \left(-\frac{dp}{d\mu} \right) d\mu. \quad (3)$$

$\overline{W}$ is a tight lower bound on the average work cost, since the above protocols are reversible. Moreover, $\overline{W}$ is associated solely with information erasure rather than any net change in the dot's internal energy μp: The change in μp is eliminated by averaging, since both protocols reset the energy level to $\mu_{\frac{1}{2}}$.

If $p(\mu)$ is interpreted as a complementary cumulative distribution function, then Eq. (3) is equivalent to half the mean absolute deviation about the median $\mu_{\frac{1}{2}}$. This provides the basis to use properties of the mean absolute deviation to disentangle contributions to $\overline{W}$ from different physical parameters, as well as a heuristic that the work cost of erasure relates directly to the spread of the occupation distribution.

Bounds on the work cost of erasure. While Eq. (3) is straightforward to integrate numerically, it is not possible to obtain a closed formula for $\overline{W}$ due to the difficulty of inverting $p(\mu)$ for $\mu_{\frac{1}{2}}$. Short of an exact formula, it will be informative to place analytic bounds on $\overline{W}$. We here present an illustrative overview of limiting cases to motivate such a bound; a formal derivation is available in SM [32].

For a quantum dot in contact with a *single* electrode with negligible lifetime broadening, $p(\mu)$ is equal to the Fermi-Dirac distribution, and its spread is characterized solely by the reservoir temperature T: In this case, the familiar Landauer bound is recovered from Eq. (3), with $\overline{W} = k_B T \ln 2$. A similar result extends to the two-reservoir case, provided that source-drain potential bias is also negligible, such that $p(\mu)$ is described by Eq. (1) with $\mu_{\frac{1}{2}} = \mu_S = \mu_D$. By linearity, Eq. (3) reduces to $\overline{W} = k_B(\gamma_S T_S + \gamma_D T_D) \ln 2$, a version of the Landauer bound involving the *average* of the reservoir temperatures, weighted by the tunneling ratios $\gamma_{S,D}$. Let us denote this thermal energy scale as E_{therm}:

$$E_{\text{therm}} = k_B(\gamma_S T_S + \gamma_D T_D) \ln 2. \quad (4)$$

If, instead, source-drain potential bias is the dominant energy scale, such that $k_B T$ and $\hbar\Gamma_{\text{tot}}$ are negligible in comparison to $\mu_S - \mu_D$, then $p(\mu)$ is effectively a sum of step functions at μ_S and μ_D, with a plateau at $p = \gamma_S$ in between. This is approximately the situation in Fig. 2(a). Supposing that $\gamma_S < \gamma_D$ (i.e., faster particle exchange with the drain than source), then $\mu_{\frac{1}{2}} \approx \mu_D$, and erasure to the $p = 1$ state is comparatively cheap (of the order $k_B T$ or $\hbar\Gamma_{\text{tot}}$). On the other hand, erasure to $p = 0$ involves raising the energy level from μ_D to μ_S at near-constant occupation $p = \gamma_S$, so that $W^0 \approx \gamma_S(\mu_S - \mu_D)$. By a mirroring argument, if instead $\gamma_S > \gamma_D$, then $W^1 \approx \gamma_D(\mu_S - \mu_D)$ and W^0 is negligible. Generally, then, in bias-dominated regimes, the average cost of erasure is approximated by a characteristic *bias energy scale*, $\overline{W} \approx E_{\text{bias}}$, given by

$$E_{\text{bias}} = \tfrac{1}{2} \min\{\gamma_S, \gamma_D\}(\mu_S - \mu_D). \quad (5)$$

Third, we can consider the limit where lifetime broadening dominates. Using a general property of the convolution, the mean absolute deviation D of the occupation distribution $p = g \star p_0$ can be bounded in terms of that of the unbroadened distribution p_0 and broadening function g, as follows: $\max\{D(g), D(p_0)\} \leqslant D(p) \leqslant D(g) + D(p_0)$ (see SM [32] for the derivation). If the broadening is such that $D(g) \gg D(p_0)$, which is the case if $\hbar\Gamma_{\text{tot}} \gg \max\{E_{\text{therm}}, E_{\text{bias}}\}$, then the average work cost of erasure is effectively set by the mean absolute deviation of the broadening function, $\overline{W} \approx \frac{1}{2} D(g)$. We will label this the *lifetime broadening energy scale*,

$$E_{\text{broad}} = \tfrac{1}{2} D(g) \equiv \tfrac{1}{2} \int_{-\infty}^{\infty} |\varepsilon - m_g| g(\varepsilon) d\varepsilon, \quad (6)$$

where m_g is the median of g. The exact dependence of E_{broad} on the tunneling rates depends on the form of the broadening distribution: For example, if g is a Gaussian with standard deviation $\hbar\Gamma_{\text{tot}}$, then $E_{\text{broad}} = \frac{\hbar\Gamma_{\text{tot}}}{\sqrt{2\pi}}$. If g is Lorentzian with scale $\hbar\Gamma_{\text{tot}}$, then the mean absolute deviation diverges, implying an unbounded energy cost for perfect erasure. However, approximate erasure to an occupation within η of 0 or 1 is still possible, with work cost $E_{\text{broad}}^{\eta} = \frac{\hbar\Gamma_{\text{tot}}}{2\pi} \ln\{\sec^2[\pi(\frac{1}{2} - \eta)]\}$, as shown in SM [32].

We have identified three independent energy scales, E_{therm}, E_{bias}, and E_{broad}, each of which emerges as the minimum average work cost of erasure $\overline{W}$ in the case that the other two vanish. This is the first main result of this Letter. It remains to treat the more general scenario where temperature, bias, and lifetime broadening all contribute nontrivially. As shown in SM [32], $\overline{W}$ can be bounded as follows:

$$\max\{E_{\text{therm}}, E_{\text{bias}}, E_{\text{broad}}\} \leqslant \overline{W} \leqslant E_{\text{therm}} + E_{\text{bias}} + E_{\text{broad}}. \quad (7)$$

This is the second main result. By the left-hand inequality, the average work cost of erasure cannot under any circumstances be made smaller than any of the three contributing energy scales as defined in Eqs. (4)–(6). The meaning of the right-hand inequality is more subtle. Certainly there is no upper limit to how much energy might be dissipated in an erasure operation when performed inefficiently. However, $\overline{W}$ relates to an ideal, thermodynamically reversible state reset. The bound here implies that, in the absence of further constraints, there is no principle preventing erasure at an average cost equal to or less than $E_{\text{therm}} + E_{\text{bias}} + E_{\text{broad}}$.

In general, neither inequality is tight. However, the upper bound on $\overline{W}$ is never more than threefold greater than the

[3]Such as at zero bias ($\mu_S = \mu_D$), or if the source and drain electrode have equal temperatures and tunneling rates.

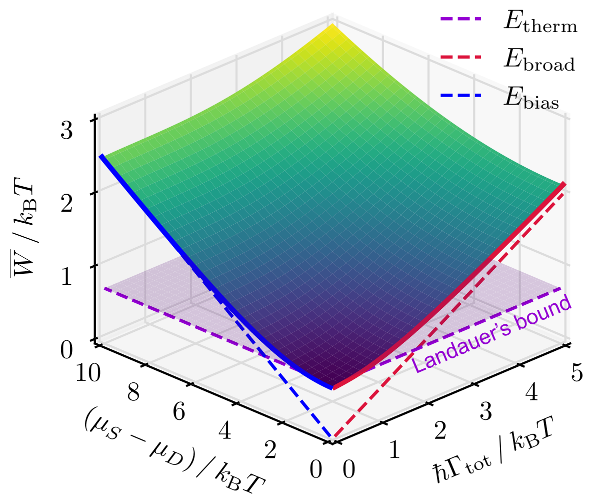

FIG. 3. The optimal average work cost of erasure $\overline{W}$ for a quantum dot in contact with two electrodes, plotted against source-drain bias $(\mu_S - \mu_D)$ and lifetime broadening $(\hbar\Gamma_{\text{tot}})$, at fixed temperature $T_S = T_D = T$. At zero bias and zero broadening, an ideal erasure process can saturate the Landauer bound, $\overline{W} = k_B T \ln 2$. However, if either $\mu_S - \mu_D$ or $\hbar\Gamma_{\text{tot}}$ exceeds a few times $k_B T$, then the work cost is significantly larger. In general, $\overline{W}$ is bounded from below by the largest out of the three characteristic energy scales E_{therm}, E_{broad}, and E_{bias} as defined in Eqs. (4)–(6), which are plotted here as dotted lines. In this plot, the source and drain tunneling rates are taken to be equal: $\Gamma_S = \Gamma_D = \frac{\Gamma_{\text{tot}}}{2}$.

lower, ensuring a correct order-of-magnitude estimate in all parameter regimes. The window becomes much narrower if any one of the three characteristic energy scales dominates. Figure 3 compares $\overline{W}$ against the bounds imposed by E_{therm}, E_{bias}, and E_{broad}. If the erasure protocol is performed in finite time, the work cost will be higher. For the particular case that the energy level is ramped at a uniform rate $\dot{\mu}$, it is shown in SM [32] that there is an additional cost $\dot{\mu}/2\Gamma_{\text{tot}}$ on top of the quasistatic work.

In experimental contexts, direct measurement of energy dissipation at microscopic scales is extremely difficult. The present approach provides a way to assess thermodynamic performance using more readily accessible measurements (temperature, voltage, and tunneling rates). Given these parameters, Eq. (7) reduces the estimation of $\overline{W}$ to a back-of-the-envelope calculation, and a more precise value is possible by integrating Eq. (3). Moreover, by separately quantifying the scale of contributions to $\overline{W}$, the approach may be used identify thermodynamic bottlenecks, a crucial step towards mitigating the cost.

Discussion. We have analyzed the thermodynamics of erasure in a model of a quantum dot charge bit, incorporating a near-ubiquitous feature of current information processing devices—that the information-bearing system is in contact with two electrodes with a potential difference. This marks a qualitative difference from the standard approach: The system is inherently out of thermodynamic equilibrium, and can at best occupy a dynamical steady state.

Landauer's bound might give the impression that the work cost of erasure can be arbitrarily low if carried out in a cold enough environment. Our results show that other factors can dominate dissipation at low temperatures. Since quantum dot devices often operate in the sub-kelvin regime, it is of practical importance to obtain a tighter bound. We find that $k_B T$ no longer represents a fixed information-energy exchange rate, with the conversion instead determined by a non-linear combination of temperatures, chemical potentials, and tunneling rates. The additional costs are intrinsic to the source-gate-drain architecture, and unavoidable even in the limit of perfect quasistatic operation. The charge bit considered here encodes information in a single electron, and a larger penalty can reasonably be expected where information is stored redundantly in multiple microscopic degrees of freedom. The quantitative understanding of the relationship between erasure costs and operating regimes in nanoscale devices is crucial for designing novel physical learning machines [38], enabling autonomous control at the nanoscale [39], and establishing the fundamental efficiency limits of computing [40].

Far from a marginal correction, non-Landauer terms are the dominant component of erasure cost in some real experimental devices. For example, Ref. [30] details a device with operating parameters $T_{S,D} = 40$ mK, $\mu_S - \mu_D = 200$ μeV, and $\Gamma_S = 6.3$ GHz, $\Gamma_D = 250$ GHz. Here, the characteristic energy scales are $E_{\text{therm}} = 2.4$ μeV, $E_{\text{bias}} = 2.5$ μeV, and $E_{\text{broad}} = 67$ μeV, and integrating (3) gives $\overline{W} = 68$ μeV (assuming Gaussian broadening). $\overline{W}$ is primarily determined by lifetime broadening in this case, with temperature and bias affecting only the second significant figure. By contrast, the device in Ref. [31] is bias- dominated: Here, T=350 mK, $\mu_S - \mu_D = 500$ μeV, $\Gamma_S = 1.75$ kHz, and $\Gamma_D = 1.45$ kHz, for which $E_{\text{therm}} = 21$ μeV, $E_{\text{bias}} = 113$ μeV, and $E_{\text{broad}} = 8.4 \times 10^{-7}$ μeV. Lifetime broadening is negligible here due to the slow tunneling rates, and thermal broadening contributes to $\overline{W}$ in the third significant figure, with $\overline{W} = 117$ μeV.

The present Letter only accounts for the work done by the field controlling the quantum dot's energy level, neglecting the energy dissipated when electrons flow from source electrode to drain (which in some cases may be partially recovered as a source of useful work [41,42]). The cost of maintaining the potential difference, in addition to the distinct bias-related contribution in Eq. (5), might be mitigated by reducing the voltage across the device. Likewise, the broadening-related cost [Eq. (6)] could be suppressed by reducing the tunneling rates between the quantum dot and electrodes. However, this leads to a compromise in the maximum possible speed of erasure, since the timescale for the dot to respond to changes in gate voltage is $\sim\frac{1}{\Gamma_{\text{tot}}}$. This principle is related to Bremermann's limit [43,44], and distinct from the dissipation which occurs when driving is fast in comparison to the equilibration rate [21]. This represents a practical thermodynamic consequence of the effective energy-time uncertainty relation [45,46]. A similar penalty due to lifetime broadening would arise for a dot which exchanges electrons with a single reservoir electrode.[4] The results indicate a possible energetic advantage for metallic dots, where the discrete energy level is replaced by a Coulomb gap in

[4]This can be seen by taking one of the tunneling rates to 0.

the density of states, with the effect of suppressing lifetime broadening [47].

While the present Letter has considered information encoded in the charge of the quantum dot, a device operating on the same principles may be used as a single-electron transistor. A key question for future work is whether lifetime broadening and potential difference have a similar influence on energy dissipation in that case, as well as how the effects scale to logic gates.

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Data availability. All code used to generate the figures is available upon reasonable request to J.D.

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