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Emergence of Constructor-Based Irreversibility in Quantum Systems: Theory and Experiment

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How irreversibility arises in a universe with time-reversal symmetric laws is a central problem in physics. In this Letter, we discuss a radically different take on the emergence of irreversibility, adopting the recently proposed constructor theory framework. Irreversibility is expressed as the requirement that a task is possible, while its inverse is not. We prove the compatibility of such irreversibility with quantum theory's time-reversal symmetric laws, using a dynamical model based on the universal quantum homogenizer. We also test the physical realizability of this model by means of an experimental demonstration with high-quality single-photon qubits.

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Introduction.—The emergence of irreversibility from time-symmetric physical laws is a central problem in contemporary physics. Indeed, there are several approaches to irreversibility in physics: statistical mechanics methods [1–3]; information-theoretic descriptions of logically irreversible tasks [4–6]; classical and quantum thermodynamics second laws [2,7–9]. In all such cases, a tension arises between the laws describing irreversible phenomena, and the time-reversal symmetry of microscopic dynamics.

In this Letter, we express irreversibility as the requirement that a transformation is possible (i.e., it can be realized limitlessly well by a system operating in a cycle), while its inverse is not. The origin of this irreversibility can be intuitively understood considering Joule's experiment [2]: while a volume of water can be heated up by mechanical means only, it is impossible to cool it down by the same means. More generally, if a transformation can be realized arbitrarily well by a machine working in a cycle, the same might not hold for the reverse transformation, even under

time-reversal symmetric laws. The concept of a cycle performing a transformation, central to thermodynamics, was generalized by von Neumann to a *constructor*—a system able to perform a given task on another system while retaining the ability to do it again. Therefore, we call the generalization of Joule's experiment irreversibility “constructor-based irreversibility.” To analyze it formally, we use *constructor theory*, a recently proposed extension of quantum computation to cover general tasks [10,11]. Compared with traditional approaches to irreversibility in quantum and classical thermodynamics, this one presents many advantages. Unlike the usual information-theoretic description, it does not suffer from the circularity between “information” and “distinguishability” definitions [11]. In contrast with quantum or classical statistical mechanics approaches [12], it does not rely on dynamical trajectories in phase space (difficult to define in quantum theory), on statistical approximations such as coarse graining or typicality arguments. With respect to quantum thermodynamics, it overcomes the issue related to the destruction of quantum coherences between system and reservoir [13] related to the two-point measurement scheme definition of work [14].

Besides, we illustrate how, surprisingly, within a qubit-based toy model this irreversibility is compatible with

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quantum theory time-reversal symmetric laws. We also provide a quantitative test of this claim by means of a quantum optics experiment.

Consider a universe made of infinite qubits, available in any state, where all unitary transformations and their transposes are allowed. A task T is the specification of a physical transformation on qubits, e.g., from a quantum state ρ_x to another one ρ_y :

$$T = \{\rho_x \rightarrow \rho_y\}, \quad (1)$$

whose transpose T^\sim is defined as

$$T^\sim = \{\rho_y \rightarrow \rho_x\}. \quad (2)$$

We will label the substrate qubit on which T is defined as Q , and the rest of the qubits as R . A constructor for T on Q is some subsystem of R enabling T , without undergoing any net change in its ability to do it again. A task is possible if there is no physical constraint on the accuracy to which a constructor can perform it, and impossible otherwise.

Constructor-based irreversibility is defined as the fact that, while T is possible, its transpose T^\sim is not. Note that thermodynamics second law can be regarded as requiring this to be true, for some tasks: this is a long-standing tradition, initiated by Planck [15] and continuing with axiomatic thermodynamics [16,17]. However, here we will focus on a more general case.

We express now the conditions allowing for a constructor for T under our unitary quantum model. A unitary transformation acting on Q and R will be denoted by $\mathcal{U}_{Q,R}$. For a fixed task T on Q and an $\epsilon > 0$, define the set of quantum states of R that can perform T to accuracy $1 - \epsilon$:

$$V_\epsilon[T] \doteq \{\rho_R : \mathcal{U}_{Q,R}(\rho_x \otimes \rho_R) \mathcal{U}_{Q,R}^\dagger = \rho, \text{Tr}_R[\rho] \in \epsilon(\rho_y)\} \quad (3)$$

being $\epsilon(\rho_y)$ the ϵ ball centered around T 's desired output state, ρ_y : $\epsilon(\rho_y) \doteq \{\sigma : F(\rho_y, \sigma) \geq 1 - \epsilon\}$, and $F(\rho_\alpha, \rho_\beta) = [\text{Tr}(\sqrt{\sqrt{\rho_\alpha}\rho_\beta\sqrt{\rho_\alpha}})]^2$ the quantum fidelity [18]. We shall denote with $\mathcal{E}[T]$ a set of N qubits prepared in a state belonging to V_ϵ , i.e., a ‘‘machine’’ capable of performing T with error ϵ .

Let us introduce a measure of how much a given $\mathcal{E}[T]$ can perform T to accuracy $1 - \epsilon$ after n repeated usages on n fresh substrates Q_1, \dots, Q_n initialized as $\rho_x^{(n)} = \rho_x \forall n$.

We define, for a given initial ρ_R state, a recursive expression for the rest state after the n th usage of $\mathcal{E}[T]$:

$$\begin{aligned} \rho_R^{(1)} &= \text{Tr}_{Q_1}[\mathcal{U}_{Q_1,R}(\rho_x^{(1)} \otimes \rho_R) \mathcal{U}_{Q_1,R}^\dagger] \\ &\vdots \\ \rho_R^{(n)} &= \text{Tr}_{Q_n}[\mathcal{U}_{Q_n,R}(\rho_x^{(n)} \otimes \rho_R^{(n-1)}) \mathcal{U}_{Q_n,R}^\dagger], \end{aligned} \quad (4)$$

where $\mathcal{U}_{Q_n,R} = \mathcal{U}_{Q_n,N} \cdots \mathcal{U}_{Q_n,1}$ denotes a sequence of unitary interactions between the n th substrate qubit and the N rest qubits emerging from the $(n-1)$ th task execution.

The worst-case-scenario steadiness of $\mathcal{E}[T]$ after n usages is defined as

$$S_{\mathcal{E}[T]}(n) \doteq \text{Inf}_{\rho_R \in V_\epsilon[T]} \{F(\rho_R, \rho_R^{(n)})\}. \quad (5)$$

Most machines lose the ability to perform their task with repeated use, so we expect $S_{\mathcal{E}[T]}(n)$ to decrease with n for a fixed ϵ . A figure of merit for $\mathcal{E}[T]$ resiliency is its relative deterioration after n usages, defined as

$$\delta_{\mathcal{E}[T]}(n) \doteq \frac{\epsilon}{S_{\mathcal{E}[T]}(n)}. \quad (6)$$

There are two conditions for a constructor realizing T to be allowed under a given unitary law $\mathcal{U}_{Q_n,R}$.

Condition (i). For any arbitrarily small $\epsilon > 0$, the set $V_\epsilon[T]$ of Eq. (3) is nonempty (i.e., the rest can perform T with arbitrarily high accuracy, once.)

Condition (ii). The relative deterioration $\delta_{\mathcal{E}[T]}(n)$ goes to zero, as ϵ goes to zero and the number n of repeated usages goes to infinity:

$$\lim_{\epsilon \rightarrow 0} \lim_{n \rightarrow \infty} \delta_{\mathcal{E}[T]}(n) = 0. \quad (7)$$

The limits order is relevant for the correct physical interpretation: for a fixed ϵ , we let n go to infinity. This indicates how resilient a machine is.

If both conditions are satisfied, then a sequence of machines $\mathcal{E}[T]$ converges to a limiting machine perfectly retaining the ability to realize T with asymptotically small error, even after n usages, for arbitrarily large n : this limiting machine is a constructor for T . A constructor generalizes the notion of catalyst in resource theory [19], with the relaxed requirement to stay within the same set of states instead of the same exact state. Under our assumptions, a constructor being allowed implies that the corresponding task is possible.

Results.—We now demonstrate the compatibility between time-reversal symmetric laws and constructor-based irreversibility with a toy model based on quantum homogenization [20,21] (see Fig. 1), showing that a task $T = \{\rho_x \rightarrow \rho_y\}$ being possible does not necessarily imply the same for its transpose T^\sim . Consider as a homogenization machine the N -qubit set $H_N[T]$, with each qubit prepared in the state ρ_y . Suppose that the substrate Q , initialized in the state ρ_x , interacts with the qubits in $H_N[T]$ one at a time via the unitary transformation

$$U_{Q,k} = \cos(\eta)I + i \sin(\eta)\Sigma_{Qk}, \quad (8)$$

where Σ_{Qk} is the SWAP gate acting on Q and the k th qubit in $H_N[T]$, with I the identity. The SWAP is defined as the gate

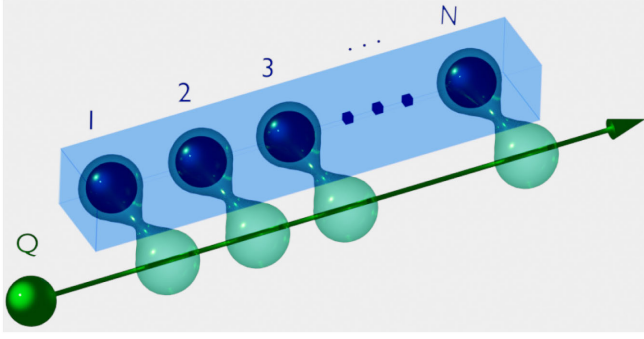


FIG. 1. Qubit-based homogenizer. A substrate qubit Q (in green) interacts with a homogenization machine (azure shaded box) composed of N qubits (in blue). The hourglasses represent the unitary partial swaps $U_{Q,k}$ ($k = 1, \dots, N$).

$\Sigma_{12}: \Sigma_{12}|\psi\rangle|\phi\rangle = |\phi\rangle|\psi\rangle$, $\forall |\psi\rangle, |\phi\rangle$ (see, e.g., Ref. [22]). This $U_{Q,k}$ is a partial swap, whose intensity depends on the real parameter η : the closer η is to $\pi/2$, the closer $U_{Q,k}$ is to a standard SWAP. For small η values, it is a way of slightly modifying the original state of Q , making it closer and closer to the target state ρ_y . The quantum homogenizer is a quantum information formalization of the well-known collision models [23–27]. These models, as well as other open-system dynamics models, see, e.g., Refs. [12,28–31], express irreversibility as emerging from statistical mechanics approximations (such as weak coupling or Markovianity) when the system of interest evolves through the interaction with an environment, typically much larger than the system itself. Here we explain irreversibility without statistical assumptions, considering instead what transformations are possible, and to what accuracy, via quantum homogenization. The state of Q after interacting with $H_N[T]$ is

$$\rho_{Q,N} = \text{Tr}_{1\dots N} \left[\tilde{\prod}_{k=N}^1 U_{Q,k} (\rho_x \otimes \rho_y^{\otimes N}) \tilde{\prod}_{k=1}^N U_{Q,k}^\dagger \right], \quad (9)$$

where $\tilde{\prod}$ denotes an ordered product.

Define now the error in performing the task on Q as

$$\epsilon_N = 1 - F(\rho_{Q,N}, \rho_y). \quad (10)$$

As the number of qubits in $H_N[T]$ goes to infinity, one has [20,21]

$$\lim_{N \rightarrow \infty} \epsilon_N = 0, \quad (11)$$

meaning that the machine $H_N[T]$ is capable of performing T perfectly for large N , thus satisfying condition (i). This holds for any task T transforming ρ_x into ρ_y . Crucially, however, not all homogenization machines satisfy condition (ii), thus failing to be constructors. Hence, not all tasks are necessarily possible. Specifically, T^\sim need not be possible, even if T is possible: this is how constructor-based irreversibility

emerges, being radically different from the standard irreversibility of the homogenizer, analyzed in Refs. [20,21] and demonstrated by various qubit implementations (see, e.g., Ref. [32]).

Consider the special case where ρ_x and ρ_y are, respectively, a pure and a maximally mixed state. In this case, task T goes in the direction of more mixedness, while T^\sim does the opposite, purifying the state. For small η , it is possible to show two facts (see Supplemental Material [33] for details): (i) As N increases, the homogenization machine $H_N[T]$ tends to be a constructor for T , because its relative deterioration goes to 0:

$$\lim_{N \rightarrow \infty} \lim_{n \rightarrow \infty} \delta_{H_N[T]}(n) = 0. \quad (12)$$

(ii) The optimal candidate to perform T^\sim , $H_N[T^\sim]$, is not a constructor for T^\sim . Specifically, one can show that

$$\lim_{N \rightarrow \infty} \lim_{n \rightarrow \infty} \delta_{H_N[T^\sim]}(n) \rightarrow \infty. \quad (13)$$

Thus, T being possible and the assumption of time-reversal symmetric laws do not imply that T^\sim must also be possible. This makes constructor-based irreversibility compatible with time-reversal symmetric laws under unitary quantum theory.

The experiment.—We provide experimental evidence of this model at work, quantifying the relative deterioration of the homogenizers for T and T^\sim and demonstrating the emergence of constructor-based irreversibility within a unitary quantum framework. Initially, we verified experimentally that the homogenizer performing the task $T = \rho_p \rightarrow \rho_m$ (being ρ_p a pure state and ρ_m a mixed one) is more efficient than the one performing the transpose task $T^\sim = \rho_m \rightarrow \rho_p$, even at the first task execution ($n = 1$). Consider two states: the pure state $\rho_p = |0\rangle\langle 0|$ and the quasimaximally mixed state $\rho_m = ((1 + \gamma)/2)|0\rangle\langle 0| + ((1 - \gamma)/2)|1\rangle\langle 1|$ (with $\gamma \ll 1$ accounting for experimental imperfections in the mixture preparation). We compare the performance of the homogenizers $H_N[T]$ and $H_N[T^\sim]$ by measuring the error ϵ of each machine in performing its task, with an experiment (Fig. 2) exploiting single-photon qubits at 1550 nm (see Supplemental Material [33] for details). Figure 3 shows the results obtained for a partial swap parameter $\eta = (\pi/4)$.

Respectively, plots (a) and (b) show, for $n = 1$, the progression of tasks T and T^\sim as the substrate Q interacts with the $k = 1, \dots, N$ qubits of the corresponding homogenizer ($N = 3$ in our setup). The reconstructed diagonal elements ρ_{00} and ρ_{11} of the Q density matrix are reported (by construction, in our case $\rho_{01} = \rho_{10} = 0$), considering for T the substrate in the initial state $\rho_p = |0\rangle\langle 0|$ and the homogenizer qubits in the mixed state $\rho_m = 0.55|0\rangle\langle 0| + 0.45|1\rangle\langle 1|$, and vice versa for T^\sim . Plot (c) shows the error ϵ in Eq. (10), indicating the discrepancy between the

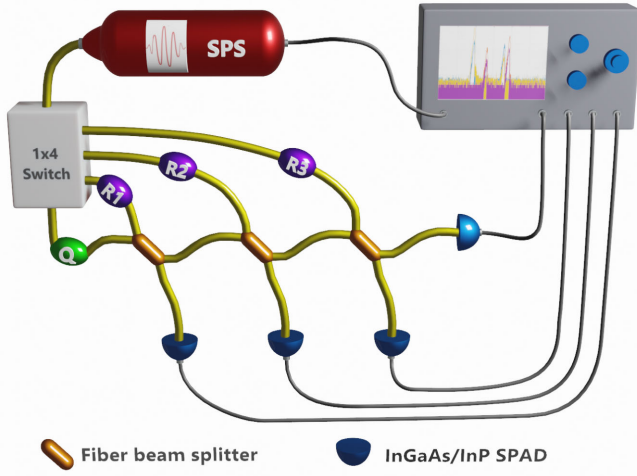


FIG. 2. Experimental setup. Heralded single photons at 1550 nm are produced by a low-noise single-photon source [34,35] and sent to a 1×4 fiber optical switch, addressing them either to the substrate path (Q) or to one of our 3-qubit homogenizer paths ($R1$, $R2$, $R3$). The single photons then meet a cascade of $N = 3$ fiber beam splitters, each implementing one of the partial swaps realizing the interaction between substrate and homogenizer. Finally, the photons are detected by free-running infrared detectors, whose output is sent to time-tagging electronics together with the heralding counts.

substrate and target state. Our results clearly show how the homogenizer for T always outperforms the one for T^\sim . We then extended our analysis to the general case $n > 1$, to verify the behavior of the relative deteriorations $\delta_{H_N[T]}(n)$ and $\delta_{H_N[T^\sim]}(n)$ [see Eq. (6), and Supplemental Material [33] for details]. To this end, we evaluated the machines steadiness with a recursive method considering, for the j th substrate state Q_j ($j = 1, \dots, n$), the machine initialized in a state as close as possible to the one of the machine outgoing the $(j - 1)$ th usage. For each j , after executing the task and tracing over Q_j in Eq. (4), the rest state $\rho_R^{(j)}$ presents some entanglement. Not being able to directly measure it, we could nevertheless observe the resulting correlations among the rest qubits, so we reconstructed these correlations (in the computational basis $\{|0\rangle, |1\rangle\}$) and reproduced them while initializing the machine state for the $(j + 1)$ th usage.

The results for both T and T^\sim are reported in Fig. 4, for two experimental η values corresponding to a weak interaction between substrate and homogenizer. Here, the relative deteriorations $\delta_{H_N[T]}(n)$ and $\delta_{H_N[T^\sim]}(n)$ are shown, providing evidence of their asymptotic limits reported in Eqs. (12) and (13). By performing numerical simulations, we studied their behavior for a limited number of N rest qubits and n machine usages, extending our analysis beyond the $N = 3$ experimental limit. We investigated both the ideal scenario, with the homogenizer qubits in an entangled state for $n > 1$ (solid curves), and the case of

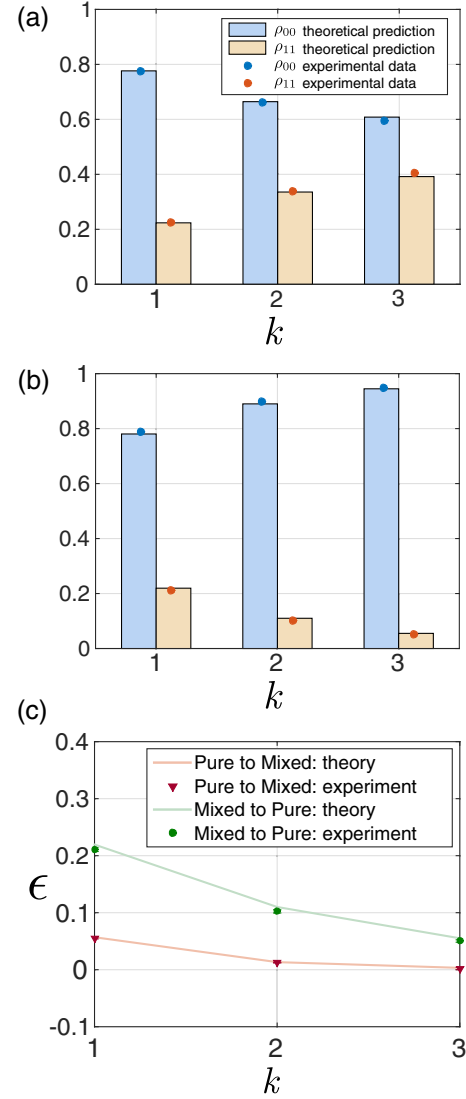


FIG. 3. Results obtained with partial swap parameter $\eta = (\pi/4)$, for the first usage of the homogenizer ($n = 1$). Panel (a): pure-to-mixed task T . The plot shows the ρ_{00} (in azure and blue) and ρ_{11} (in yellow and red) elements of the substrate Q density matrix, initially in the pure state $\rho_p = |0\rangle\langle 0|$, after each partial swap $U_{Q,k}$ with one of the $N = 3$ homogenizer qubits in the mixed state $\rho_m = 0.55|0\rangle\langle 0| + 0.45|1\rangle\langle 1|$ (experimentally measured), showing the substrate state evolution induced by the homogenizer. Bars: theoretical predictions; dots: experimentally reconstructed values, reported with the associated uncertainties (within dots size). Panel (b): mixed-to-pure task T^\sim , being the substrate initial state $\rho_m = 0.55|0\rangle\langle 0| + 0.45|1\rangle\langle 1|$ and the homogenizer qubits state $\rho_p = |0\rangle\langle 0|$. Panel (c): error ϵ for both T (in orange) and T^\sim (in green). Lines: theoretical expectations. Dots: experimental values, with associated uncertainties (within dots size).

the rest qubits forming a separable state for each usage of the homogenizer (dashed curves). For the sake of completeness, we also considered the approximation (dotted curves) of small swap intensity η and a homogenizer

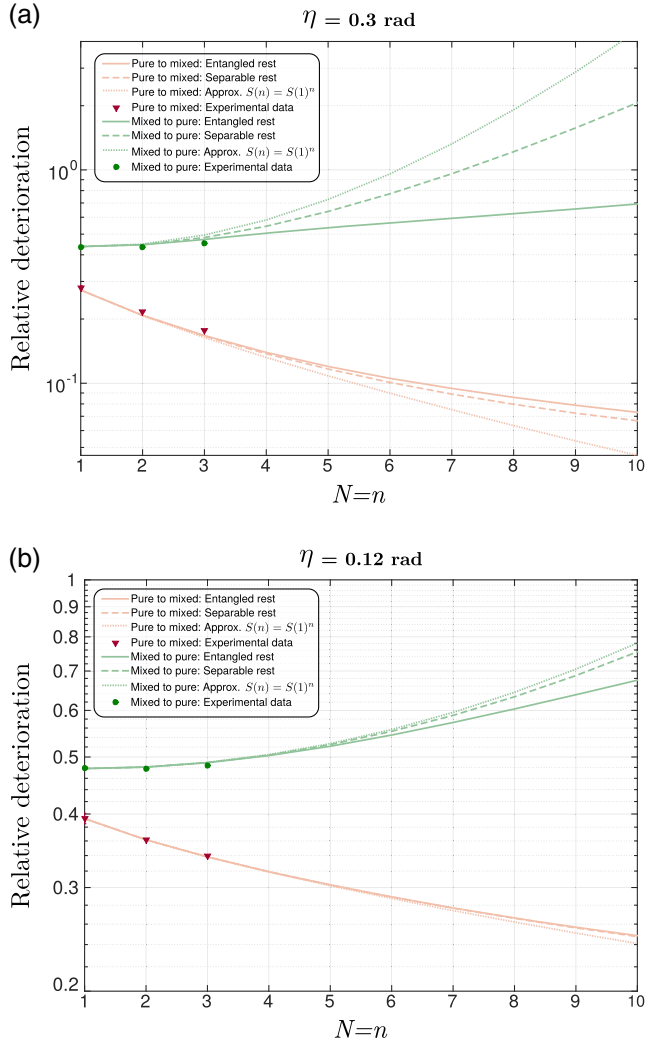


FIG. 4. Constructor-based irreversibility demonstration. Plots (a) and (b) show, for $\eta = 0.3$ and $\eta = 0.12$, respectively, the relative deterioration of the homogenizer for T and T^\sim , as a function of the number of machine qubits N and usages n . Solid curves: theoretical predictions, considering the rest entangled for $n > 1$. Dashed curves: predictions obtained by approximating the rest, for $n > 1$, as an ensemble of qubits in a separable state. Dotted curves: approximation considering for each $j = 1, \dots, n$ a separable rest state, in the limit of small η and with $S_{\mathcal{E}[T]}(n) \approx S_{\mathcal{E}[T]}(1)^n$. Triangles (dots): experimental values obtained for T (T^\sim), with the experimental uncertainty bars below the data points size.

steadiness of the form $S_{\mathcal{E}[T]}(n) \approx S_{\mathcal{E}[T]}(1)^n$, with $\rho_R^{(n)}$ taken as the tensor product of the reduced density operators of the rest qubits after the n th usage. Such approximation allows finding analytical solutions for $\delta_{H_N[T]}(n)$ and $\delta_{H_N[T^\sim]}(n)$, satisfying the conditions in Eqs. (12) and (13), respectively (details in Supplemental Material [33]).

Figure 4 shows that, for task T , the relative deterioration $\delta_{H_N[T]}(n)$ steadily decreases for growing n, N , qualifying $H_N[T]$ as a proper constructor for T , according to Eq. (12).

Conversely, we observe that $\delta_{H_N[T^\sim]}(n)$ diverges for increasing n, N , in agreement with Eq. (13), hence $H_N[T^\sim]$ fails to be a constructor for T^\sim . We can conclude that, in the constructor theory framework, the task T is “possible,” while its counterpart T^\sim need not be: this is what makes the process corresponding to the task T potentially irreversible.

Conclusions.—We proposed a novel take on the old-age problem of reconciling irreversibility with reversible unitary dynamics with a radically different approach, considering the irreversibility based on tasks possibility or impossibility rather than on statistical considerations about dynamical trajectories being permitted or disallowed. This irreversibility extends the thermodynamical one to a general information-theoretic scenario, thus representing a significant contribution to the development of a generalized quantum thermodynamics [7,36–39]. We used the constructor theory framework, stating that a certain task T being possible does not imply the same for its transpose T^\sim . Here, we illustrated this idea with a specific example, providing experimental evidence of this mechanism at work. Our experimental results demonstrate that the homogenizer implementing T always outperforms its counterpart for the reverse task T^\sim , and that the machine for T^\sim suffers a much higher degradation than the one realizing T , ultimately not satisfying condition (ii) and thus failing to be a constructor. This gives a clear proof of the compatibility of constructor-based irreversibility with unitary quantum theory, providing a frame for the emergence of thermodynamical irreversibility in quantum mechanics [40–45]. In perspective, our work prompts us to seek new interpretations of existing entropy measures by studying the connection of this irreversibility definition with other ones, e.g., in quantum and classical statistical mechanics.

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