Universal Work Extraction as Invariant Selection

A Quantum Collapse Geometry Interpretation of State-Agnostic Quantum Thermodynamics

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Abstract

Recent results in quantum thermodynamics demonstrate that the optimal asymptotic work extraction rate—characterized by the Helmholtz free energy—can be achieved without any prior knowledge of the input quantum state[1]. We provide a structural reinterpretation of this result within the framework of Quantum Collapse Geometry (QCG). In this perspective, universal work extraction arises from selection of invariant structure under admissible transformations rather than from detailed state-dependent optimization. The free energy is interpreted as an invariant functional over admissible relational configurations, while the universal protocol acts as a state-independent selection map (interpreted as collapse-selection). This interpretation preserves all operational results while clarifying why full state knowledge is not required for optimal performance, and situates state-agnostic thermodynamics within a broader collapse-first ontology.

1 Introduction

Determining the maximum work extractable from a quantum system is a central problem in quantum thermodynamics. Standard results establish that, in the asymptotic i.i.d. regime, the optimal extractable work per copy is given by the free energy:

$$\beta W_\infty(\rho) = D(\rho\|\tau), \tag{1}$$

where τ is the Gibbs state.

Conventional derivations assume that the experimenter has complete knowledge of the input state ρ, enabling the construction of tailored protocols. Recent work shows that this assumption is unnecessary: there exist *state-agnostic* (universal) protocols that achieve the same optimal rate without any knowledge of ρ [1].

This result challenges the intuition that detailed state knowledge is required for optimal thermodynamic performance.

2 Universal Work Extraction

The key result establishes the existence of a fixed sequence of thermal operations $\{\Lambda_n\}$ such that, for any input state ρ,

$$\beta W_\infty^{\text{agnostic}}(\rho) = D(\rho\|\tau), \tag{2}$$

matching the optimal state-aware rate.

The construction proceeds by:

- exploiting permutation symmetry across many copies,
- applying Schur pinching to obtain a structured diagonal form,
- estimating coarse-grained quantities (e.g., relative entropy),
- executing a fixed protocol independent of the full state description.

Thus, optimal work extraction depends only on coarse invariant quantities rather than full microscopic knowledge.

3 QCG Framework: Selection and Invariance

In Quantum Collapse Geometry (QCG), physical structure arises through selection under constraint. The framework consists of:

- a relational configuration space Σ,
- a collapse-selection operator $\Phi : \Sigma \to \Sigma$,
- a projection $P : \Sigma \to \mathcal{O}$.

Observable structure corresponds to invariant sectors:

$$\mathrm{Fix}(\Phi) = \{x \in \Sigma \mid \Phi(x) = x\}. \tag{3}$$

Physical quantities are interpreted as functionals defined over these invariant sectors, rather than properties of individual configurations.

4 Mapping Universal Work Extraction to QCG

The universal work extraction protocol admits a natural interpretation within QCG:

Quantum Thermodynamics	**QCG Interpretation**
Unknown state ρ	Relational configuration $x \in \Sigma$
Multiple copies $\rho^{\otimes n}$	Ensemble access to configuration space
Universal protocol Λ_n	State-independent collapse-selection map Φ
Schur pinching / coarse operations	Admissibility filtering
Relative entropy $D(\rho\|\tau)$	Invariant functional over $\mathrm{Fix}(\Phi)$
Extracted work	Observable residue $P(\mathrm{Fix}(\Phi))$

In this interpretation:

- the protocol does not reconstruct the state,
- it filters configurations into admissible sectors,
- the extracted work reflects invariant structure shared across configurations.

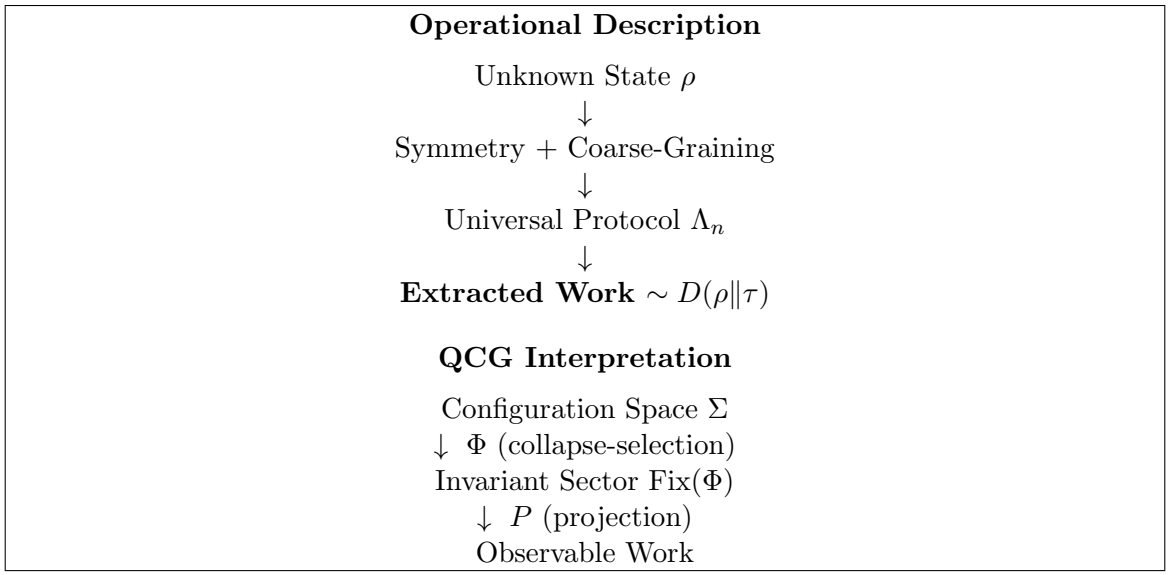

Figure 1: Universal work extraction as invariant selection. The protocol does not reconstruct the input state, but selects collapse-stable structure whose invariant functional determines the extractable work.

5 Diagrammatic Interpretation

6 Interpretation: Invariance Without Description

The central implication is that optimal thermodynamic performance depends only on invariant structure, not on full state description.

Within QCG:

- detailed microstate information is not required for selection,
- collapse eliminates distinctions irrelevant to invariant functionals,
- observable quantities depend only on persistent structure.

Thus, the equivalence of state-aware and state-agnostic performance arises naturally: both access the same invariant sector.

7 Implications

This perspective suggests:

- Thermodynamic resources are determined by invariant structure, not microscopic detail.
- Information acquisition (e.g., tomography) is not required for optimal extraction in asymptotic regimes.
- Similar universality may appear in other resource theories where invariant functionals govern optimal performance.
- The distinction between description and operation is fundamental: optimal physical processes need not reconstruct underlying states.

8 Conclusion

Universal work extraction demonstrates that optimal thermodynamic behavior does not require knowledge of the underlying quantum state. Within QCG, this result is interpreted as a manifestation of invariant selection under admissible collapse dynamics.

This reframing preserves all operational results while clarifying their structural origin: physical performance is governed by invariant structure rather than detailed description.

References

[1] Kaito Watanabe and Ryuji Takagi. "Universal work extraction in quantum thermodynamics". In: *Nature Communications* 17.1 (2026), p. 1857.