Convex geometry of quantum resource quantification

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Convex geometry of quantum resource quantification

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Abstract
We introduce a framework unifying the mathematical characterisation of different measures of general quantum resources and allowing for a systematic way to define a variety of faithful quantifiers for any given convex quantum resource theory. The approach allows us to describe many commonly used measures such as matrix norm-based quantifiers, robustness measures, convex roof-based measures, and witness-based quantifiers together in a common formalism based on the convex geometry of the underlying sets of resource-free states. We establish easily verifiable criteria for a measure to possess desirable properties such as faithfulness and strong monotonicity under relevant free operations, and show that many quantifiers obtained in this framework indeed satisfy them for any considered quantum resource. We derive various bounds and relations between the measures, generalising and providing significantly simplified proofs of results found in the resource theories of quantum entanglement and coherence. We also prove that the quantification of resources in this framework simplifies for pure states, allowing us to obtain more easily computable forms of the considered measures, and show that many of them are in fact equal on pure states. Further, we investigate the dual formulation of resource quantifiers, which provide a characterisation of the sets of resource witnesses.

We present an explicit application of the results to the resource theories of multi-level coherence, entanglement of Schmidt number \( k \), multipartite entanglement, as well as magic states, providing insight into the quantification of the four resources by establishing novel quantitative relations and introducing new quantifiers, such as a measure of entanglement of Schmidt number \( k \) which generalises the convex roof–extended negativity, a measure of \( k \)-coherence which generalises the \( \ell_1 \) norm of coherence, and a hierarchy of norm-based quantifiers of \( k \)-partite entanglement generalising the greatest cross norm.
Keywords: resource theories, resource quantification, entanglement measures, coherence measures

(Some figures may appear in colour only in the online journal)

1. Introduction

Many physical phenomena in quantum information science have gone from being of purely theoretical interest to enjoying a variety of uses as resources in quantum information processing tasks. The developments sparked an investigation into the mathematical formulation of such resource theories, aiming to characterise the quantum states and operations that one can use to perform the physical tasks. Starting with the resource theory of entanglement, which found use in a wide variety of quantum information processing, quantum communication, and quantum computing protocols [1], the recent years have seen the establishment of resource theories of athermality [2], asymmetry [3, 4], purity [5], coherence [3, 6–8], nonclassicality [9, 10], EPR steering [11], contextuality [12], magic states [13, 14], and others, including more general mathematical formulations of resource theories [15–21].

In particular, it is crucial to be able to quantify the given resource, allowing us to discriminate which quantum states are the most useful in the given physical task. Throughout the development of the resource theory of entanglement, various measures were established [1, 22], many of which have been adapted to other resource theories recently [7, 8, 10, 17, 20, 23, 24]. However, defining and characterising the measures of a given quantum resource is usually cumbersome—the investigation of such functions typically has to be approached in a resource-dependent way, and properties such as faithfulness and monotonicity of the quantifiers have to be explicitly verified. Moreover, although some connections between the various quantities are known, there are very few known results which provide a common framework relating them and their features together.

1.1. Summary of the results

In this work, we introduce a unifying formalism based on the convex geometry of the underlying sets of quantum states, significantly simplifying the construction and characterisation of quantifiers of general quantum resources. We employ the concept of gauge functions, a fundamental tool in functional and convex analysis [25–27], to establish a consolidated view of many resource measures. In particular, we show that many commonly used and well-known quantifiers—such as ones based on matrix norms, measures built through the convex roof, the so-called robustness measures, as well as various witness-based quantifiers—are all examples of such gauge functions, allowing us to relate them in a common geometric framework. This lets us establish an extensive family of quantifiers for any given quantum resource, introduce easily verifiable criteria for a measure to satisfy desirable properties such as faithfulness and strong monotonicity under relevant free operations, and generalise known measures to new quantum resources very easily. Further, we show that many relations and bounds between the measures, some of which known in the resource theories of entanglement and coherence, are in fact universal among quantum resources, and the proofs of such properties can be simplified in the present framework.

The formalism of this paper applies to general finite-dimensional resource theories with a convex set of resource-free states, which is a common and intuitive assumption [16, 17]. A particularly useful case of such resources, and one that we will focus on, is when the set of
free states is obtained as the convex hull of free pure states. More specifically, given a set of pure state vectors $\mathcal{V}$ (these can be e.g. product pure states in the resource theory of entanglement, or the reference basis vectors in the resource theory of coherence), we define the set of interest—the free states $\mathcal{S}^+_{\text{free}}$—as the convex hull of projectors $|\psi\rangle\langle\psi|$ with each $|\psi\rangle \in \mathcal{V}$. The quantities of interest are then the *gauge functions* corresponding to different sets, which can be understood as an alternative notion of ‘distance’ from the given set. Gauge functions have a number of appealing properties such as a rich structure of convex duality, allowing many quantifiers to admit a simplified characterisation when expressed in this way.

The simplest and easiest to compute gauge function is $\Gamma_{\mathcal{V}}$, that is, the gauge based on the set $\mathcal{V}$. This gauge can be used to quantify pure-state resources—for instance, in the resource theory of bipartite entanglement, it is equal to the sum of Schmidt coefficients [28], while in the resource theory of coherence it corresponds to the $\ell_1$ norm [7]. The quantification of resources for general mixed states has a more complex structure and one can establish a variety of different gauges which all form valid quantifiers of the given resource. In fact, we can show that many well-known monotones belong to the gauge function formalism: these are the robustness measures, generalising the fundamental entanglement measures of robustness $R^S_{\mathcal{S}_{\text{ent}}}$ [29] and global robustness $R^G_{\mathcal{S}_{\text{ent}}}$ [17, 23, 30]; the norm-based measures $\Gamma_{\mathcal{S}_{\text{ent}}}$, which include the greatest cross norm of entanglement [31, 32] and the $\ell_1$ norm of coherence [7]; the convex roof–based measures $\Gamma^\cup_{\mathcal{S}_{\text{ent}}}$, such as the convex roof–extended negativity [33] and the coherence concurrence [34, 35]; as well as several other measures, such as many experimentally-friendly families of witness-based quantifiers known from the theory of entanglement [36–38].

The crucial application of the framework is that the often extremely technical and cumbersome resource-dependent proofs of properties, bounds, and analytical expressions for the resource measures are not needed, as the convex geometric framework provides simplified proof methods and establishes relations which hold regardless of the considered resource.

To begin with, the gauge function formalism helps establish a fundamental property of the above quantities: for any considered quantum resource, all of the gauge-based measures are in fact valid resource quantifiers, satisfying desirable properties such as faithfulness, convexity, and strong monotonicity under relevant classes of operations. Further, the framework provides easily verifiable conditions for any other gauge-based quantity to share the same properties, applicable e.g. to various witness-based measures.

We then establish several quantitative relations between the gauges for any given convex quantum resource, such as the inequalities

$$R^S_{\mathcal{S}_{\text{ent}}} (\rho) \geq \Gamma_{\mathcal{S}_{\text{ent}}} (\rho) - 1 \geq R^G_{\mathcal{S}_{\text{ent}}} (\rho) \quad \Gamma^\cup_{\mathcal{S}_{\text{ent}}} (\rho) \geq \Gamma_{\mathcal{S}_{\text{ent}}} (\rho)$$

(1)

which immediately allow us to relate the introduced quantifiers with each other, generalising results from resource theories of bipartite entanglement and coherence to general quantum resources. Furthermore, in the convex geometric framework each gauge function has an associated dual gauge function, allowing us to establish several bounds and equivalences which can be useful in the characterisation of the dual sets of resource witnesses. We additionally relate the gauges with other fundamental quantifiers such as the distance- and witness-based measures, showing that more connections can be generalised to arbitrary convex resource theories.

We further show that the bounds obtained above can in fact be tight: for any convex resource theory, the considered quantifiers reduce to the simplified gauge $\Gamma_{\mathcal{V}}$ on pure states:

$$\Gamma_{\mathcal{S}} (|\psi\rangle\langle\psi|) = R^S_{\mathcal{S}_{\text{ent}}} (|\psi\rangle\langle\psi|) + 1 = \Gamma^\cup_{\mathcal{S}_{\text{ent}}} (|\psi\rangle\langle\psi|) = \Gamma_{\mathcal{V}} (|\psi\rangle) = |\langle\psi|\psi\rangle|^2.$$

(2)
These relations, frequently a non-trivial fact to establish for a particular resource theory, show that the quantification of pure-state resources is always simplified. Note that the gauge function $A_V$ is often significantly easier to compute than the general forms of the quantifiers, in many cases leading to an analytical characterisation of pure-state resource measures.

To exemplify the application and usefulness of the framework, we consider some representative resource theories—bipartite and multipartite entanglement, quantum coherence, and magic states—obtaining new results in the quantification of the resources, and in particular novel bounds and analytical formulas for quantifiers of bipartite entanglement of Schmidt rank $k$, $k$-partite entanglement, and $k$-coherence. In addition to shedding new light on quantifiers already defined in the literature, we introduce several new measures, such as: a measure of multi-level quantum coherence which generalises the $\ell_1$ norm of coherence, faithful quantifiers of magic, measures of bipartite entanglement of Schmidt number $k$ and $k$-partite entanglement which generalise the convex roof-extended negativity, as well as a class of norms which generalise the greatest cross norm to the hierarchy of $k$-partite entanglement, with computable formulas for genuine multipartite entanglement.

The paper is structured as follows. In section 2, we review methods from convex geometry and analysis, and provide an introduction to the concept of gauge functions as well as the convex roof. In section 3 we apply the framework to quantum states, showing how to define measures for any convex resource theory and establishing results concerning the computability and interrelations between many such quantities. Section 4 contains a characterisation of atomic gauges as quantifiers of a given quantum resource, establishing easily verifiable conditions for properties such as faithfulness and strong monotonicity, as well as relating the gauge functions to measures defined through resource witnesses and distance-based quantifiers. Finally, section 5 contains an explicit application of our results to several quantum resource theories as mentioned above.

2. Gauges and norms

2.1. Atomic gauges

The definitions in this section follow standard literature, in particular Rockafellar [26, sections 14 and 15]; see also [39–41], where much of this information is reviewed and expanded on. We will use $\mathbb{R}_+$ to denote non-negative reals and $\mathbb{R}_{++}$ to denote positive reals.

A set $S$ is called a cone if it contains any non-negative scalar multiple of its elements, i.e., $s \in S \Rightarrow \lambda s \in S \forall \lambda \in \mathbb{R}_+$. A convex cone $S$ is then a cone which contains any conic combination of elements in $S$ (non-negative linear combination).

Consider a finite-dimensional real vector space with an inner product $\langle \cdot, \cdot \rangle$. Given a set $S$, we define its polar set $S^\circ$ as

$$S^\circ = \{ x \mid \langle x, s \rangle \leq 1 \ \forall s \in S \} \quad (3)$$

and its dual cone $S^*$ as

$$S^* = \{ x \mid \langle x, s \rangle \geq 0 \ \forall s \in S \} . \quad (4)$$

The polar set and dual cone are always closed and convex, regardless of whether $S$ is. Note that the polar set of a cone $K$ is given by $K^\circ = -K^*$.

The gauge function $\gamma_S$ for a set $S$ (also known as the Minkowski functional) is defined as

$$\gamma_S(x) = \inf \{ \lambda \in \mathbb{R}_+ \mid x \in \lambda S \} = \inf_{s \in S} \{ \lambda \in \mathbb{R}_+ \mid x = \lambda s \} \quad (5)$$
where we note that the effective domain of $\gamma_S$ is the cone generated by $S$, i.e. \( \{ \mu s \mid \mu \in \mathbb{R}_+, s \in S \} =: \mathbb{R}_+ S \), and we follow the convention that $\gamma_S(x) = \infty \forall x \notin \text{dom}(\gamma_S)$, or equivalently $\inf \emptyset = \infty$.

An important example of gauge functions are norms, which are the gauge functions of their unit balls. Norms are defined as finite functions satisfying the following axioms: absolute homogeneity (of degree 1), subadditivity, and positivity everywhere except the origin. This corresponds to gauge functions of sets $S$ which are convex, compact, centrally symmetric ($S = -S$), and such that $0 \in \text{int}(S)$. In general, we have the following relations between sets and their corresponding gauges [26, 42]:

<table>
<thead>
<tr>
<th>$S$</th>
<th>$\gamma_S$</th>
<th>$\forall x \in \text{dom}(\gamma_S)$, it holds that</th>
</tr>
</thead>
<tbody>
<tr>
<td>Convex</td>
<td>Convex, positively homogeneous</td>
<td>$\gamma_S(\alpha x) = \alpha \gamma_S(x) \forall \alpha \in \mathbb{R}_+$</td>
</tr>
<tr>
<td>Closed</td>
<td>Closed (lower semicontinuous)</td>
<td>${ x \mid \gamma_S(x) \leq \alpha }$ is closed $\forall \alpha \in \mathbb{R}$</td>
</tr>
<tr>
<td>Bounded</td>
<td>Positive everywhere except 0</td>
<td>$\gamma_S(x) &gt; 0 \forall x \neq 0$</td>
</tr>
<tr>
<td>Centrally symmetric</td>
<td>Symmetric (even)</td>
<td>$\gamma_S(x) = \gamma_S(-x)$</td>
</tr>
<tr>
<td>$0 \in \text{int}(S)$</td>
<td>Finite everywhere</td>
<td></td>
</tr>
</tbody>
</table>

where we note that evenness together with positive homogeneity implies absolute homogeneity, and convexity with positive homogeneity implies subadditivity.

Following the terminology of [27] and subsequent works, given a compact set $C$ we define the atomic gauge as the gauge function of the convex hull $\text{conv}(C)$:

$$\Gamma_C(x) = \gamma_{\text{conv}(C)}(x)$$  \hspace{1cm} (6)

which can also be written as an optimisation over conic combinations of elements of $C$:

$$\Gamma_C(x) = \inf \left\{ \lambda \mid x = \lambda \sum c_i a_i, a_i \in C, c_i \in \mathbb{R}_+, \sum c_i = 1 \right\}$$

$$= \inf \left\{ \sum c_i \mid x = \sum c_i a_i, a_i \in C, c_i \in \mathbb{R}_+ \right\}. \hspace{1cm} (7)$$

By Carathéodory’s theorem, it suffices to consider combinations of at most $d$ elements, with $d$ denoting the dimension of the vector space. Note that this function need not be symmetric or finite everywhere, and so it only defines a valid norm when the linear span of $C$ is the whole space and $C$ is centrally symmetric. The domain of $\Gamma_C$ is the conic hull of $C$, given by $\mathbb{R}_+ \text{conv}(C) = C^{**}$. Notice that $\text{conv}(C)^o = C^o$ and $\text{conv}(C)^* = C^*$.

An important property of the atomic gauge is that if $0 \in \text{conv}(C)$, the unit ball of $\Gamma_C$ is given exactly by $\text{conv}(C)$, and each such unit ball uniquely determines its corresponding atomic gauge—more generally, all closed convex gauge functions are in a one-to-one correspondence with closed convex sets containing the origin. In general, the unit ball of a gauge is given by

$$\{ x \mid \Gamma_C(x) \leq 1 \} = C^{oo} = \text{cl} (\text{conv}(C \cup \{0\})) \hspace{1cm} (8)$$

where cl denotes closure, which in particular means that $\Gamma_C = \Gamma_C^{oo}$.

The polar function of $\Gamma_C$ is defined as

$$\Gamma_C^*(x) = \sup \{ \langle x, a \rangle \mid \Gamma_C(a) \leq 1 \}$$

$$= \sup_{a \in C^{oo}} \langle x, a \rangle$$

$$= \max \left\{ 0, \sup_{a \in C} \langle x, a \rangle \right\}. \hspace{1cm} (9)$$
where the last equality follows from the fact that the supremum of a linear functional over a compact convex set is reached at an extremal point of the set. The polar of the atomic gauge is precisely the atomic gauge for the polar set $C^\circ$, i.e., $\Gamma_{C^\circ} = \gamma_{C^\circ}$, and in fact $\Gamma_C = \gamma_C$ as $C^\circ$ is already a closed convex set containing the origin ($C^{\circ \circ \circ} = C^\circ$). The polarity operation induces a one-to-one symmetric correspondence between closed convex gauge functions, which means that any atomic gauge of a compact set is uniquely determined by its polar. When $\Gamma_C$ defines a valid norm, $\Gamma_{C^\circ}$ is its dual norm.

A set $C$ is bounded if and only if $0 \in \text{int}(C)$; dually, $C^\circ$ is bounded if and only if $0 \in \text{int}(C)$. For any bounded set $C$, $\Gamma_{C^\circ}$ then has full domain. Note that the polarity operation is inclusion-reversing, i.e., $C_1 \subseteq C_2 \Rightarrow C_1^\circ \supseteq C_2^\circ$: this means that $\Gamma_{C_1}(x) \geq \Gamma_{C_2}(x)$ $\forall x \in \text{dom}(\Gamma_{C_1})$ and $\Gamma_{C_2}^\circ(y) \leq \Gamma_{C_1}^\circ(y)$ $\forall y \in \text{dom}(\Gamma_{C_1}^\circ)$ for such sets.

Since $0 \in C^\circ$ for any set $C$, by considering the polar function of the set $C^\circ$ we can also write

$$\Gamma_C(x) = \Gamma_{C^\circ\circ}(x) = \sup_{a \in C^\circ} \langle x, a \rangle$$

which we will refer to as the dual formulation of the atomic gauge.

We note that all atomic gauges also satisfy some properties which are well-known for norms, such as the generalised Cauchy–Schwarz inequality $\langle \langle x, y \rangle \rangle \leq \Gamma_C(x) \Gamma_C^\circ(y)$ $\forall x \in \text{dom}(\Gamma_C)$, $y \in \text{dom}(\Gamma_C^\circ)$.

### 2.1.1 Complex vector spaces

In a complex vector space, we define the polar with respect to the real inner product $\text{Re} \langle x, y \rangle$, and similarly for other definitions. A generalisation of the concept of a centrally symmetric set is then a balanced set, that is $S$ s.t. $s \in S \Rightarrow \xi s \in S \forall \xi \in \mathbb{C} : |\xi| = 1$. In particular, for a balanced set we have $\Gamma_S(x) = \Gamma_S(\xi x)$ for all $\xi$ as above, and we can then take a simplified definition of a polar function:

$$\Gamma_S^*(x) = \max \left\{ 0, \sup_{a \in S} \text{Re} \langle x, a \rangle \right\} = \sup_{a \in S} |\langle x, a \rangle| .$$

Any convex, balanced, compact set which spans the whole space defines a valid norm. We will henceforth only encounter balanced sets in complex vector spaces, so we do not expand on other properties and definitions—see e.g. [43] for more general cases.

### 2.2 Nuclear gauges

Consider now the vector space of matrices in $\mathbb{C}^{d \times d}$ with the Hilbert–Schmidt inner product $\langle X, Y \rangle = \text{Tr} X^\dagger Y$. Note that the subspace of Hermitian matrices defines a real inner product space. Let $\mathbb{H}$ denote $d \times d$ Hermitian matrices (the dimension will be omitted when it is unambiguous), $\mathbb{H}_+$ positive semidefinite matrices, and $\mathbb{H}_+$ positive definite matrices. We will use the Dirac notation $|x\rangle$ to refer to vectors in $\mathbb{C}^d$ which are not necessarily normalised.

Given atomic gauges $\Gamma_X$ and $\Gamma_Y$ for balanced compact sets $X, Y \subseteq \mathbb{C}^d$, one can define the nuclear gauge for $M \in \mathbb{C}^{d \times d}$ as [40, 44]

$$N_{X,Y}(M) = \inf \left\{ \sum_i \Gamma_X(|x_i\rangle) \Gamma_Y(|y_i\rangle) \mid M = \sum_i |x_i\rangle \langle y_i| \right\} .$$

This provides a general way of inducing matrix gauges by vector gauges, and indeed it is a valid norm when $\Gamma_X$ and $\Gamma_Y$ are both norms [40]. Some basic examples include the trace norm (when $\Gamma_X = \Gamma_Y = \|\cdot\|_1$) and the element-wise $\ell_1$ norm ($\Gamma_X = \Gamma_Y = \|\cdot\|_{\ell_1}$).
To relate the concepts of the atomic and nuclear gauges explicitly, we have the following result, generalising a lemma of [45, 46].

**Proposition 1.** Given balanced compact sets $\mathcal{X}, \mathcal{Y} \subseteq \mathbb{C}^d$, the induced nuclear gauge $N_{\mathcal{X}, \mathcal{Y}}$ is in fact the atomic gauge for the set

$$C = \{ |a\rangle \langle b| \mid |a\rangle \in \mathcal{X}, |b\rangle \in \mathcal{Y} \}.$$  \hfill (13)

**Proof.** First, we will show that the nuclear gauge is the atomic gauge $\Gamma_S$ corresponding to set

$$S = \{ |a\rangle \langle b| \mid \Gamma_\mathcal{X}(|a\rangle) \leq 1, \Gamma_\mathcal{Y}(|b\rangle) \leq 1 \}
= \{ |a\rangle \langle b| \mid |a\rangle \in \text{conv}(\mathcal{X}), |b\rangle \in \text{conv}(\mathcal{Y}) \}.$$  \hfill (14)

We begin by noting that $N_{\mathcal{X}, \mathcal{Y}}$ indeed is convex [26, 5.4], and the properties of closedness, positivity everywhere except 0, and positive homogeneity follow straightforwardly from the properties of $\Gamma_\mathcal{X}$ and $\Gamma_\mathcal{Y}$ [26, 9.2.1]. $N_{\mathcal{X}, \mathcal{Y}}$ is therefore a valid gauge function corresponding to a convex, compact set.

Now, from the definition (12) it holds that if $M \in S^\infty$, i.e. $M = \sum_i c_i |x_i\rangle \langle y_i|$, with $c_i \in \mathbb{R}^+$, $\sum_i c_i \leq 1$, $|x_i\rangle \in \text{conv}(\mathcal{X})$, and $|y_i\rangle \in \text{conv}(\mathcal{Y})$, then we necessarily have

$$N_{\mathcal{X}, \mathcal{Y}} \left( \sum_i c_i |x_i\rangle \langle y_i| \right) \leq \sum_i \Gamma_\mathcal{X}(\sqrt{c_i}|x_i\rangle) \Gamma_\mathcal{Y}(\sqrt{c_i}|y_i\rangle) = \sum_i c_i \Gamma_\mathcal{X}(|x_i\rangle) \Gamma_\mathcal{Y}(|y_i\rangle) \leq 1,$$

and therefore $S^\infty$, the unit ball of $\Gamma_S$, is contained in the unit ball of $N_{\mathcal{X}, \mathcal{Y}}$. For the opposite inclusion, we have that if $N_{\mathcal{X}, \mathcal{Y}}(M) \leq 1$, then by the closedness of $\mathcal{X}$ and $\mathcal{Y}$ there exists a decomposition $M = \sum_i |x_i\rangle \langle y_i|$ such that

$$1 \geq N_{\mathcal{X}, \mathcal{Y}}(M) = \sum_i \Gamma_\mathcal{X}(|x_i\rangle) \Gamma_\mathcal{Y}(|y_i\rangle) \geq \sum_i \Gamma_S(|x_i\rangle \langle y_i|) \geq \Gamma_S \left( \sum_i |x_i\rangle \langle y_i| \right)$$

which follows by the convexity of $\Gamma_S$. We have therefore established that $N_{\mathcal{X}, \mathcal{Y}}(M) \leq 1 \iff \Gamma_S(M) \leq 1 \iff M \in S^\infty$, and since there is a one-to-one correspondence between closed convex gauge functions and their unit balls, the gauges must be equal [26, section 15].

Notice that $C \subseteq S$ by construction, which means that $\Gamma_C(M) \geq \Gamma_S(M)$. On the other hand, any $S \in S$ can be written as $S = |a\rangle \langle b|$ with $|a\rangle = \sum_i c_i |a_i\rangle$ and $|b\rangle = \sum_j d_j |b_j\rangle$, where $c_i, d_j \in \mathbb{R}^+, |a_i\rangle \in \mathcal{X}, |b_j\rangle \in \mathcal{Y}$, and $\sum_i c_i = \sum_j d_j = 1$. But then we have that $S = \sum_{ij} c_i d_j |a_i\rangle \langle b_j|$ with $\sum_{ij} c_i d_j = 1$, which means that $S \in \text{conv}(C)$ and so we have that $S \subseteq \text{conv}(C)$. This implies that $\Gamma_S(M) \geq \gamma_{\text{conv}(C)}(M) = \Gamma_C(M)$, and so the gauges have to be equal. \hfill \blacksquare

### 2.3. Convex roof

Let $S$ be a compact convex set in a real finite-dimensional vector space, and let $\text{ext}(S)$ be the set of its extremal points, such that $S = \text{conv}(\text{ext}(S))$. Given a function $f$ defined on $\text{ext}(S)$, we now would like to consider a function $f'$ defined on the whole set $S$ such that the two functions are equal on $\text{ext}(S)$—we will call such functions extensions of $f$. A particularly useful class of them is defined as follows:
Definition 2. A function $f^\cup : \mathcal{S} \to \mathbb{R}_+$ is a roof extension of $f : \text{ext} (\mathcal{S}) \to \mathbb{R}_+$, if for every point $x \in \mathcal{S}$ there exists at least one extremal convex decomposition $\{c_i, \pi_i\}$ of the form $x = \sum_i c_i \pi_i$ with $c_i \in \mathbb{R}_+$, $\sum_i c_i = 1$, $\pi_i \in \text{ext} (\mathcal{S})$, such that $f^\cup (x) = \sum_i c_i f(\pi_i)$.

The justification for the terminology of roofs can be understood by noting that if we know a set of extremal points $\{\pi_1, \ldots, \pi_k\}$ which constitutes an optimal decomposition for some $x \in \mathcal{S}$, the roof extension $f$ will be affine on the convex hull of these points—that is, the same set of points will be an optimal decomposition for any other convex combination thereof. This means that the graph of $f$ consists of flat (affine) pieces covering the set $\mathcal{S}$, not unlike a roof covering a floor.

Out of these roof extensions, we are particularly interested in the following.

Theorem 3 (Uhlmann [47]). If a convex roof extension $f^\cup$ of $f : \text{ext} (\mathcal{S}) \to \mathbb{R}_+$ exists, then it is unique and satisfies the following properties:

(i) $f^\cup$ is the pointwise largest convex extension of $f$ from $\text{ext} (\mathcal{S})$ to $\mathcal{S}$

(ii) $f^\cup$ is the pointwise smallest roof extension of $f$ from $\text{ext} (\mathcal{S})$ to $\mathcal{S}$

(iii) $f^\cup$ is given by

$$f^\cup (x) = \inf \left\{ \sum_i c_i f(\pi_i) \middle| \sum_i c_i \pi_i = x, \sum_i c_i = 1, c_i \in \mathbb{R}_+ \right\}$$

with the infimum taken over all extremal convex decompositions $\{c_i, \pi_i\}$.  

Since we will be dealing with functions $f : \text{ext} (\mathcal{S}) \to \mathbb{R}_+ \cup \{\infty\}$, we extend the definition by taking $f^\cup (x) = \infty$ when $x \notin \text{conv} (\text{dom} f)$. For a function $g$ already defined on the whole set $\mathcal{S}$, we define its convex roof extension as the convex roof extension of the restriction of $g$ to $\text{ext} (\mathcal{S})$—if $g$ is convex, it is then clear from the above theorem that $g^\cup (x) \geq g(x) \forall x$.

Note also the related concept of the concave roof $f^\cap$: it is the pointwise smallest concave extension (or pointwise largest roof extension) of $f$, and can be calculated by replacing the minimisation with a maximisation in equation (17):

$$f^\cap (x) = \sup_{\{c_i, \pi_i\}} \left\{ \sum_i c_i f(\pi_i) \middle| \sum_i c_i \pi_i = x, \sum_i c_i = 1, c_i \in \mathbb{R}_+ \right\}.$$  

One can notice a similarity between the concept of the convex roof and the convex envelope (also known as the convex hull or the largest convex underestimator). For a function $g$ which is already defined on the whole convex set $\mathcal{S}$, its convex envelope is the largest convex function majorised by $g$. In practice, finding the convex envelope means that the optimisation in equation (17) is performed over all decompositions of $x$ into $s_i \in \mathcal{S}$, instead of $\pi_i \in \text{ext} (\mathcal{S})$ as in the case of the convex roof extension. For this reason, in quantum information literature the convex envelope has sometimes been referred to as the mixed convex roof, identifying $\text{ext} (\mathcal{S})$ with the set of pure quantum states. Note that the convex envelope of a concave function defined on $\mathcal{S}$ coincides with its convex roof extension, since the infimum of any concave function over a bounded convex set is equal to the infimum over its extremal points [26, 32.2].

The relation between the convex roof and the formalism of atomic gauges can be made explicit with the following result.

Proposition 4. Given a compact set $\mathcal{C} \subseteq \text{ext} (\mathcal{S})$, for any $x \in \mathcal{S}$ we have

$$\Gamma_{\mathcal{C}} (x) = \gamma_{\mathcal{C}}^\cup (x).$$  

(19)
Proof. Noting that \( \gamma_C \) is finite only on its effective domain \( \mathbb{R}_+ C \), we see that the domain of \( \gamma_C^\prime \) is extended to \( \text{conv}(\mathbb{R}_+ C) = C^{**} \), which is indeed the domain of \( \Gamma_C^\prime \). It follows from theorem 3 that \( \gamma_C^\prime \) is a convex function. By the compactness of \( C \), \( \gamma_C \) is closed and positive everywhere except 0, and together with the positive homogeneity of \( \gamma_C \) it guarantees that \( \gamma_C^\prime \) is closed, positive everywhere except 0, and positively homogeneous. We then have that \( \gamma_C^\prime \) is indeed a valid gauge function corresponding to a convex, compact set.

From equation (17) it is explicit that if \( x \in C^{00} \), i.e. \( x \) can be expressed as a convex combination of 0 and elements \( \{ \pi_i \} \) such that \( \gamma_C(\pi_i) \leq 1 \forall i \), then \( \gamma_C^\prime(x) \leq 1 \). On the other hand, if \( \gamma_C^\prime(x) \leq 1 \), then there exists an extremal decomposition \( \{ c_i, \pi_i \} \) such that

\[
1 \geq \sum_i c_i \gamma_C(\pi_i) = \sum_i c_i \Gamma_C(\pi_i) \geq \Gamma_C \left( \sum_i c_i \pi_i \right),
\]

where the equality follows since any extremal element cannot be expressed as a convex combination of other extremal elements by definition, which means that we necessarily have \( \gamma_C(\pi) = \Gamma_C(\pi) \forall \pi \in \text{ext}(S) \), and the last inequality follows by the convexity of \( \Gamma_C \). Therefore \( \gamma_C^\prime(x) \leq 1 \iff \Gamma_C(x) \leq 1 \iff x \in C^{00} \), and since there is a one-to-one correspondence between closed convex gauge functions and their unit balls, the gauges must be equal [26, section 15].

The application of proposition 4 is particularly useful for sets of positive semidefinite matrices, where we identify \( S \) with \( \mathbb{H}_+ \) and \( \text{ext}(S) \) with rank-one positive semidefinite matrices. As an explicit example, given a balanced set \( X \subseteq \mathbb{C}^d \), let us define \( C \subseteq \text{ext}(\mathbb{H}_+) \) as

\[
C = \{ |a\rangle \langle a| \mid |a\rangle \in X \}.
\]

Then, one can easily see that \( \gamma_C(|x\rangle \langle x|) = \gamma_X(|x\rangle \langle x|)^2 \), which allows us to express the atomic gauge function of \( C \) as

\[
\Gamma_C(P) = \gamma_C^\prime(P) = \inf \left\{ \sum_i p_i \gamma_X(|x_i\rangle \langle x_i|)^2 \mid P = \sum_i p_i |x_i\rangle \langle x_i|, \sum_i p_i = 1, p_i \in \mathbb{R}_+ \right\}.
\]

We will extend this idea by considering other convex roof extensions for sets of matrices in the succeeding sections.

3. Atomic gauges for sets of quantum states

We consider quantum states defined over a finite-dimensional Hilbert space, which we will identify with \( \mathbb{C}^d \) with the standard inner product. We denote by \( \mathbb{D} \) the set \( \{ X \in \mathbb{H}_+ \mid \langle 1, X \rangle = 1 \} \) of valid \( d \times d \) density matrices in the real vector space of \( d \times d \) Hermitian matrices \( \mathbb{H} \).

One of the essential elements of the characterisation of a general resource theory are the free states, that is, states not possessing a given resource. We therefore begin by defining the set of resource-free normalised pure state vectors \( \mathcal{V} \subseteq \mathbb{C}^d \), which we will assume to be non-empty. Another intuitive assumption is that the set \( \mathcal{V} \) should be compact, which ensures the continuity of the given resource theory [17]. Since the global phase factor \( e^{i\theta}|\psi\rangle \) of a quantum state \( |\psi\rangle \) is physically irrelevant, we further assume that \( |\psi\rangle \in \mathcal{V} \) implies \( e^{i\theta}|\psi\rangle \in \mathcal{V} \forall \theta \in \mathbb{R}_+ \), which means the set is balanced and so \( 0 \in \text{conv}(\mathcal{V}) \). We then get the atomic gauge
\[ \Gamma_V(|\psi\rangle) = \inf \left\{ \sum_i c_i \left| |\psi\rangle = \sum_i c_i |v_i\rangle, |v_i\rangle \in \mathcal{V}, c_i \in \mathbb{R}_+ \right\} \]  

(23)

\[ \Gamma^\circ_V(|\psi\rangle) = \sup_{|\omega\rangle \in \mathcal{V}} |\langle \psi|\omega\rangle|. \]  

(24)

Under the assumptions above, \( \Gamma_V \) is a proper norm whenever \( 0 \notin \text{int}(\text{conv}\mathcal{V}) \), i.e. \( \text{span}(\mathcal{V}) = \mathbb{C}^d \). This property is very desirable for the set \( \mathcal{V} \), as we will see later, but we do not assume it to hold in all cases.

Given the set \( \mathcal{V} \) defined at the level of vectors, we now define our set of interest: the set of resource-free density matrices, given by the convex hull of the set \( \mathcal{S}_+ = \{ |\psi\rangle\langle\psi| \mid |\psi\rangle \in \mathcal{V} \} \subseteq \mathbb{D} \).

(25)

Since all density matrices which do not lie in \( \text{conv}(\mathcal{S}_+) \) are resourceful states in the given resource theory, we would now like to use the set \( \mathcal{S}_+ \) to introduce a gauge function which could effectively quantify this resource. The atomic gauge \( \Gamma_{\mathcal{S}_+} \) itself is not very useful: since the domain of this function is \( \mathcal{S}_+^* = \mathbb{R}_+ \text{conv}(\mathcal{S}_+) \) (the convex cone generated by \( \mathcal{S}_+ \)) and all density operators lie in the hyperplane defined by \( \langle I, \rho \rangle = 1 \), there are actually no density operators in the domain of \( \Gamma_{\mathcal{S}_+} \) which do not lie in the convex hull of \( \mathcal{S}_+ \). That is, for any \( \rho \in \mathbb{D} \) we have

\[ \Gamma_{\mathcal{S}_+} (\rho) \leq 1 \quad \text{if} \quad \rho \in \text{conv}(\mathcal{S}_+), \]

\[ \Gamma_{\mathcal{S}_+} (\rho) = \infty \quad \text{if} \quad \rho \notin \text{conv}(\mathcal{S}_+). \]  

(26)

We will now look at ways of circumventing this problem by making a different choice of the gauge function to use.

Note, however, that the polar gauge \( \Gamma^\circ_{\mathcal{S}_+} \) has full domain since \( \mathcal{S}_+ \) is bounded.

### 3.1. Selection of gauges

Our aim now is to define a choice of non-trivial atomic gauges, which we can later use as resource quantifiers.

An intuition for the possible choices of suitable quantifiers can be obtained by looking at the simple example where \( \mathcal{V} \) is taken to be the set of all normalised pure state vectors. In this case, we have \( \text{conv}(\mathcal{S}_+) = \mathbb{D} \), and the gauge \( \Gamma_\mathbb{D} \) can be thought of as the trace norm \( \|\cdot\|_1 \) but defined only on the limited domain \( \mathbb{R}_+ \mathbb{D} = \mathbb{H}_+ \). A natural way to extend the domain of this function is to symmetrise the set under consideration, and consider the gauge \( \Gamma_{\mathbb{D} \cup (-\mathbb{D})} \) instead—since the origin is now contained in the convex hull of the set, the function takes finite values for all Hermitian matrices. In fact, \( \Gamma_{\mathbb{D} \cup (-\mathbb{D})} \) is simply equal to the trace norm itself \([54]\), with the domain extended to \( \mathbb{H} \). One can go a step further and, instead of limiting ourselves to the real vector space of Hermitian matrices, define the set \( \mathcal{S} = \{ |a\rangle\langle b| \} \) where \( |a\rangle, |b\rangle \) are any normalised vectors. The gauge \( \Gamma_{\mathcal{S}} \) is then precisely the trace norm \( \|\cdot\|_1 \) in its most general formulation, which has full domain in \( \mathbb{C}_d \times \mathbb{H}_+ \). In these simple examples, we have seen that different ways of extending the domain of the gauge \( \Gamma_{\mathcal{S}_+} \) actually correspond to the same function (on their effective domains), and so there is little ambiguity in the choice of the appropriate extension. This does not, however, hold in more general cases, and so it becomes useful to be able to characterise all the different possible gauges that we can obtain from the initial set \( \mathcal{V} \).

Returning to the case of general quantum resources, we can follow the above motivation and consider the atomic gauge with respect to the symmetrised set \( \mathcal{S}_+ \cup (-\mathcal{S}_+) \). This extends...
the domain of the gauge function to span($S_+$), that is, the vector space generated by $S_+$. We then get the gauge
\[
\Gamma_{S_+ \cup (-S_+)}(\rho) = \inf_{\sigma \in S_+ \cup (-S_+)} \left\{ \sum_i c_i \mid \rho = \sum_i c_i \sigma, \ c_i \in \mathbb{R}_+ \right\}
\]
\[
= \inf_{|v|, |w|} \left\{ \sum_i |c_i| \mid \rho = \sum_i c_i |v_i\rangle \langle v_i|, \ c_i \in \mathbb{R} \right\}
\]
\[
\Gamma^\circ_{S_+ \cup (-S_+)}(\rho) = \sup \left\{ |\langle v| \rho |v\rangle| \mid |v\rangle \in V \right\}.
\]
(27)

The above can be equivalently expressed as
\[
\Gamma_{S_+ \cup (-S_+)}(\rho) = \inf_{X_i \in \mathbb{H}} \left\{ \sum_i \Gamma_{S_+ \cup (-S_+)}(X_i) \mid \rho = \sum_i X_i, \ \text{rank}(X_i) = 1 \right\}
\]
\[
= \inf_{|x_i\rangle \in \mathbb{C}^d} \left\{ \sum_i |c_i| \Gamma_{S_+ \cup (-S_+)}(|x_i\rangle \langle x_i|) \mid \rho = \sum_i c_i |x_i\rangle \langle x_i|, \ c_i \in \mathbb{R} \right\}.
\]
(28)

$\Gamma_{S_+ \cup (-S_+)}$ defines a valid norm for Hermitian matrices as long as span($S_+$) = $\mathbb{H}$.

Another straightforward way to define a quantifier is to consider instead the set
\[
S = \{ |a\rangle \langle b| \mid |a\rangle \in V, \ |b\rangle \in V \},
\]
which we note to be balanced in the complex vector space $\mathbb{C}^{d \times d}$ with the Hilbert–Schmidt inner product. The corresponding atomic gauge is:
\[
\Gamma_S(\rho) = \inf_{|v\rangle, |w\rangle \in V} \left\{ \sum_i |c_i| \mid \rho = \sum_i c_i |v_i\rangle \langle w_i|, \ c_i \in \mathbb{R}_+ \right\}
\]
\[
= \inf_{|x_i\rangle, |y_i\rangle \in \mathbb{C}^d} \left\{ \sum_i \Gamma_V(|x_i\rangle \langle y_i|) \Gamma_\mathcal{V}(|y_i\rangle \langle y_i|) \mid \rho = \sum_i |x_i\rangle \langle y_i| \right\}
\]
(30)

where the second equality follows by identifying the gauge with the nuclear gauge introduced previously. Indeed, if we have that span($V$) = $\mathbb{C}^d$, then $\Gamma_V$ is a norm and therefore $\Gamma_S$ defines a valid nuclear norm for $\mathbb{C}^{d \times d}$.

A further possibility is to consider the values of the gauge function $\Gamma_V$ defined for pure states, which is in general simpler to quantify than gauge functions defined at the level of density matrices. This function can then be extended to density matrices through the convex roof. To ensure homogeneity at the level of projectors $|\psi\rangle \langle \psi|$, we will take the extension of $\Gamma_V(|\psi\rangle \langle \psi|)^2$—in fact, this choice makes such an extension equal to $\Gamma_{S_+}$ on dom($\Gamma_{S_+}$). We then get:
\[
\Gamma^\uparrow_{S_+}(\rho) := (\Gamma^2_V)^\cup(\rho) = \inf \left\{ \sum_i p_i \Gamma_V(|x_i\rangle \langle x_i|) \mid \rho = \sum_i p_i |x_i\rangle \langle x_i|, \ \sum_i p_i = 1, \ p_i \in \mathbb{R}_+ \right\}
\]
(31)

The convex roof extension can therefore be regarded as a natural extension of $\Gamma_{S_+}$ out of its limited domain, since it will be finite for any density matrix as long as span($V$) = $\mathbb{C}^d$. We can characterise it as a gauge function, similarly to proposition 4, as follows.
Proposition 5. The convex roof extension $\Gamma^\cup_{S_+}$ is the atomic gauge for the set

$$S^\cup_+ = \{ |a\rangle \langle a| \ |a| \in \text{conv}(\mathcal{V}) \}.$$ (32)

Proof. First, notice that rank-1 projectors $|\psi\rangle\langle\psi|$ cannot be expressed as a positive combination of elements of the form $\sum_i |x_i\rangle\langle x_i|$ except for the choice of a single vector $|x_i\rangle = e_i^d|\psi\rangle$. By the balancedness of $\mathcal{V}$, this gives $\gamma_{S_+}(|\psi\rangle\langle\psi|) = \gamma_{\text{conv}(\mathcal{V})}(|\psi\rangle) = \Gamma_{\mathcal{V}}(|\psi\rangle)^2$. The claim then follows by proposition 4. \[\blacksquare\]

Before we proceed with the characterisation of the introduced atomic gauges, let us make explicit the effective domains on which the functions are finite.

<table>
<thead>
<tr>
<th>Gauge</th>
<th>Effective domain</th>
<th>Note</th>
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<tbody>
<tr>
<td>$\Gamma_{\mathcal{V}}$</td>
<td>$\text{span}(\mathcal{V})$</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{S_+}$</td>
<td>$S^*<em>+ \cap \Delta = \text{conv}(S</em>+)$</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{S_+ \cup (-S_+)}$</td>
<td>$\text{span}(S_+)$</td>
<td>If $\text{relint}(\text{conv}S_+) \neq \emptyset$, then $\Delta \subseteq \text{dom}(\Gamma_{S_+ \cup (-S_+)}$</td>
</tr>
<tr>
<td>$\Gamma_{\mathcal{S}_+}$</td>
<td>$\text{span}(S)$</td>
<td>If $\text{span}(\mathcal{V}) = C^d$, then $\Delta \subseteq \text{dom}(\Gamma_{\mathcal{S}_+})$</td>
</tr>
<tr>
<td>$\Gamma^{-}<em>{\mathcal{S}</em>+}$</td>
<td>$S^{**} \cap C^d$</td>
<td>If $\text{span}(\mathcal{V}) = C^d$, then $\Delta \subseteq \text{dom}(\Gamma^{-}<em>{\mathcal{S}</em>+})$</td>
</tr>
<tr>
<td>$\Gamma^0_{\mathcal{S}_+}$</td>
<td>$\mathbb{H}$</td>
<td>$C^{d \times d}$</td>
</tr>
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</table>

In the above, $\text{relint}(\text{conv}S_+)$ is the interior of $\text{conv}(S_+)$ relative to $\Delta$. The set $S^\cup_+ \cap$ can be understood as the set of positive semidefinite matrices supported on the subspace spanned by $\mathcal{V}$.

We also remark that in general we have

$$\Gamma_{S_+}(\rho) \geq \Gamma_{S_+ \cup (-S_+)}(\rho) \geq \Gamma_{S}(\rho)$$

and reverse inequalities for the polar gauges, which follows from the set inclusion of their corresponding unit balls.

Theorem 6. For pure states $|\psi\rangle\langle\psi| s.t. |\psi\rangle \in \text{span}(\mathcal{V})$, we have

$$\Gamma^\cup_{S_+}(|\psi\rangle\langle\psi|) = \Gamma_{\mathcal{V}}(|\psi\rangle)^2$$

$$\Gamma_{S}(|\psi\rangle\langle\psi|) = \Gamma_{\mathcal{V}}(|\psi\rangle)^2.$$ (34)

For arbitrary pure states we also have

$$\Gamma^{-}_{S_+}(|\psi\rangle\langle\psi|) = \Gamma^{-}_{\mathcal{V}}(|\psi\rangle)^2$$

$$\Gamma^0_{S_+}(|\psi\rangle\langle\psi|) = \Gamma^0_{\mathcal{V}}(|\psi\rangle)^2.$$ (35)

Proof. We have shown the case of $\Gamma^\cup_{S_+}$ in the proof of proposition 5.

For $\Gamma_{S}$, notice that by the compactness of $\mathcal{V}$ there exist $\lambda^* \in \mathbb{R}_+$ and $|\psi^*\rangle \in \text{conv}(\mathcal{V})$ such that

$$\lambda^* = \min \{ \lambda \in \mathbb{R}_+ \ | \ |\psi\rangle \in \lambda \text{conv}(\mathcal{V}) \} = \Gamma_{\mathcal{V}}(|\psi\rangle).$$ (36)
with $|\psi\rangle = \lambda^* |\nu^*\rangle$. This gives $|\psi\rangle \langle\psi| = \lambda^* \xi |\nu^*\rangle \langle\nu^*| \in \text{conv}(S)$, and so

$$
\Gamma_V(|\psi\rangle \langle\psi|) = \lambda^* \geq \sup \{ |\eta\rangle \langle\eta| : \eta \in \text{conv}(S) \} = \Gamma_S(|\psi\rangle \langle\psi|). \quad (37)
$$

Now, from the dual formulation of the atomic gauge we get

$$
\Gamma_S(|\psi\rangle \langle\psi|) = \sup \{|\langle\psi|X\psi\rangle| : X \in S^o \}
$$

$$
\geq \sup \{|\langle\psi|X\phi\rangle| : |\phi\rangle \in V^o \}
$$

$$
= \sup \{|\langle\psi|x\rangle|^2 : |x\rangle \in V^o \}
$$

$$
= \Gamma_V(|\psi\rangle \langle\psi|)
$$

(38)

since $|x\rangle \in V^o \Rightarrow |x\rangle \langle x| \in S^o$, and so the claim follows.

The case of $\Gamma^o_S$ follows immediately from the definition. For $\Gamma^o_S$, we have

$$
\Gamma^o_S(|\psi\rangle \langle\psi|) = \sup \{|\langle\psi|X\psi\rangle| : X \in S^o \}
$$

$$
= \left( \sup_{|x\rangle \in V} |\langle\psi|x\rangle|^2 \right)^2
$$

$$
= \Gamma^o_V(|\psi\rangle \langle\psi|)
$$

(39)

since we are dealing with compact sets of non-negative real numbers.

We can also note a stronger property that

$$
\Gamma_S(|\psi\rangle \langle\psi|) = \Gamma_V(|\psi\rangle \langle\psi|) \Gamma^o_V(|\psi\rangle \langle\psi|)
$$

$$
\Gamma^o_S(|\psi\rangle \langle\psi|) = \Gamma^o_V(|\psi\rangle \langle\psi|) \Gamma^o_V(|\psi\rangle \langle\psi|).
$$

(40)

**Proposition 7.** For positive semidefinite matrices $P$, we have

$$
\Gamma^o_S(P) = \Gamma^o_S(\Gamma^o_P) = \Gamma^o_S(\Gamma^o_P) = \Gamma^o_S(\Gamma^o_P) = \Gamma^o_{S^o \cup (-S^o)}(P)
$$

(41)

We will make use of the following lemma.

**Lemma 8.** For any $P \in \mathbb{H}_+$, it holds that

$$
\sup \{|\langle a|P|b\rangle| : |a\rangle, |b\rangle \in V \} = \sup \{|\langle a|P|a\rangle| : |a\rangle \in V \}.
$$

(42)

**Proof.** First, notice that the left-hand side clearly cannot be smaller than the right-hand side. The other inequality can be shown e.g. following [50]. By the compactness of $V$, there exists a $|\nu^*\rangle$ which realises the maximum on the right-hand side. Writing $P$ in its spectral decomposition $P = \sum_i \chi_i |p_i\rangle \langle p_i|$, we then have for any $|a\rangle, |b\rangle$ that

$$
|\langle a|P|b\rangle|^2
$$

$$
\leq \left( \sum_i \chi_i |\langle a|p_i\rangle|^2 \right)^2 \left( \sum_i \chi_i |\langle b|p_i\rangle|^2 \right)
$$

$$
\leq \left( \sum_i \chi_i |\langle a^*|p_i\rangle|^2 \right)^2 \left( \sum_i \chi_i |\langle a|p_i\rangle|^2 \right)
$$

$$
= \langle a^*|P|a^*\rangle^2
$$

(43)

using the Cauchy–Schwarz inequality, which proves the lemma.
Proof (of Proposition 7). By the above lemma, one immediately obtains \( \Gamma_{S_+}^0 (P) = \Gamma_{S}^0 (P) \) from the definitions. It is also straightforward to see that \( \Gamma_{S_+\cup(-S_+)}^0 (P) \) follows in a similar way. For \( \Gamma_{S_+}^0 \), we have that
\[
\Gamma_{S_+}^0 (P) = \sup \{ \langle P, Z \rangle \mid Z \in \text{conv}(S_+^d) \}
\]
where the fourth equality follows since each \( \langle \nu_i | P | \nu_i \rangle \) is a convex quadratic form in \( |\nu_i\rangle \) by the positive semidefiniteness of \( P \) [51], and the maximum of a convex function over a bounded convex set is reached at an extremal point of the set [26, 32.2].

\[
3.1.1. \text{Remark: hierarchies of resources.} \quad \text{Quantum resources are often considered in a hierarchy, where states are not simply divided into free and resourceful states, but there exist several levels of resourcefulness. Examples include bipartite entanglement (where one can consider the Schmidt rank, measuring how many levels of two quantum systems are entangled), multipartite entanglement (where one can quantify the number of parties entangled together), or quantum coherence (where one is interested in the number of levels of a system which are in a superposition).}
\]

In general, we can consider the resource rank of a pure state, that is, the function
\[
r_V(|\psi\rangle) = \min \left\{ n \in \mathbb{N} \mid |\psi\rangle = \sum_{i=1}^{n} c_i |\nu_i\rangle, \ c_i \in \mathbb{R}_+, \ |\nu_i\rangle \in \mathcal{V} \right\}
\]
which is well-defined for any state as long as \( \text{span}(\mathcal{V}) = \mathbb{C}^d \). The definition can be extended to mixed states as the resource number, generalising the Schmidt number familiar from entanglement theory [52]:
\[
r_{S_+} (\rho) = \min \left\{ n \in \mathbb{N} \mid \rho = \sum_{i} c_i |\nu_i\rangle\langle \nu_i|, \ c_i \in \mathbb{R}_+, \ |\nu_i\rangle \in \mathcal{V}, \ \sum_{i} c_i = 1, \ r_V(|\nu_i\rangle) \leq n \right\}.
\]
The resource number is equal to 1 if and only if \( \rho \in \text{conv}(S_+) \).

An intuitive understanding of the atomic gauge functions is then as convex relaxations of the resource number. In particular, it follows easily from the definitions that
\[
\begin{align*}
\Gamma_{S_+} (|\psi\rangle\langle \psi|) &= \Gamma_{V} (|\psi\rangle\langle \psi|) \geq \Gamma_{S} (|\psi\rangle\langle \psi|), \\
r_{S_+} (\rho) &= \left[ \Gamma_{S_+}^0 (\rho) \right] = \left[ \Gamma_{S}^0 (\rho) \right] \\
\end{align*}
\]
that is, the gauge functions can be used to lower-bound the resource number of a given state. This kind of convex relaxation bears particular resemblance to the problem of minimising the rank of a matrix, for which an efficient convex surrogate function relaxing the rank is the corresponding atomic gauge, the trace norm [53].

A more direct application of gauge functions to resource hierarchies, establishing quantifiers for each level of the hierarchy, can be obtained by considering all quantum states with \( r_{\mathcal{S}_+}(\rho) \leq k \) as the free states and all states with \( r_{\mathcal{S}_+}(\rho) > k \) as resourceful. We will consider explicit examples of such application to resource theories of entanglement and coherence in section 5.

### 3.2. Base norms and robustness

If the set \( \mathcal{S}_+ \) spans the whole space of Hermitian matrices, the gauge \( \Gamma_{\mathcal{S}_+ \cup (-\mathcal{S}_+)} \) defines a valid norm for \( \mathbb{H} \) called the base norm [54]. Base norms have found a variety of uses in state and channel discrimination [49, 55–57]. More generally, one can consider other gauges of the type \( \Gamma_{\mathcal{S}_+ \cup X} \) with \( X \) being another set satisfying some desired properties. A connection between such gauges and measures commonly used in entanglement theory—robustness and negativity—was noticed by Vidal and Werner [28] as well as Rudolph [58] and later briefly expanded on by Plenio and Virmani [22]. We extend and further generalise the relation between gauges of this type and resource quantifiers.

Consider a general quantity \( R_{\mathcal{X}}^{\mathcal{S}_+}(\rho) \), which we will refer to as the robustness with respect to the closed set \( \mathcal{X} \subseteq \mathbb{D} \):

\[
R_{\mathcal{X}}^{\mathcal{S}_+}(\rho) = \inf_{\omega \in \text{conv}(\mathcal{X})} \left\{ s \in \mathbb{R}_+ \mid \rho + s\omega \in \mathcal{S}_+^{**} \right\}
= \inf_{\sigma \in \text{conv}(\mathcal{S}_+)} \left\{ s \in \mathbb{R}_+ \mid \rho - (1 + s)\sigma \in (-\mathcal{X})^{**} \right\}
\]

(48)

where the second equality follows by noting that \( \rho \in \mathbb{D} \) together with \( \mathcal{X} \subseteq \mathbb{D} \) mean that \( \rho = r\sigma - s\omega \Rightarrow r = (1 + s) \). The robustness can be understood as the smallest amount of mixing with a state in the set \( \text{conv}(\mathcal{X}) \) necessary in order for the resulting renormalised mixed state to be in \( \text{conv}(\mathcal{S}_+) \) [29]. In the case that no feasible \( s \in \mathbb{R}_+ \) exists, we take \( \inf \emptyset = \infty \) as before.

In terms of gauge functions, the robustness can be expressed as the gauge corresponding to an unbounded set of the form:

\[
R_{\mathcal{X}}^{\mathcal{S}_+}(\rho) = \Gamma_{\mathcal{S}_+ \cup (-\mathcal{X})}^{**}(\rho) = \Gamma_{\mathcal{S}_+ \cup (-\mathcal{X})}^{**}(\rho) - 1.
\]

(49)

Alternatively, by introducing the generalised inequality \( A \succeq_{\mathcal{X}} B \iff A - B \in \mathcal{X}^{**} \) we can also write the above as

\[
R_{\mathcal{X}}^{\mathcal{S}_+}(\rho) = \inf_{\omega \in \text{conv}(\mathcal{X})} \left\{ s \in \mathbb{R}_+ \mid \rho \succeq_{\mathcal{S}_+} -s\omega \right\}
= \inf_{\sigma \in \text{conv}(\mathcal{S}_+)} \left\{ s \in \mathbb{R}_+ \mid \rho \preceq_{\mathcal{X}} (1 + s)\sigma \right\}.
\]

(50)

We note the similarity of this expression to geometric concepts such as the Thompson metric [59, 60] and Hilbert’s metric [61, 62], the latter having been applied to the study of distinguishability norms in quantum information [49].

Comparing this with the expression for \( \Gamma_{\mathcal{S}_+ \cup (-\mathcal{X})} \), which we can write as
\[
\Gamma_{S,+ \cup (-\mathcal{X})}(\rho) = \inf \{ \lambda^+ + \lambda^- \mid \rho = \lambda^+ \sigma - \lambda^- \omega, \lambda^\pm \in \mathbb{R}_+, \sigma \in \text{conv}(S_+), \omega \in \text{conv}(\mathcal{X}) \},
\]
we have that \( \rho \in \mathbb{D} \Rightarrow \lambda^+ - \lambda^- = 1 \) and so the following relation holds:
\[
R_{S,+}^q(\rho) = \frac{\Gamma_{S,+ \cup (-\mathcal{X})} - 1}{2}.
\]

Two choices of the set \( \mathcal{X} \) will be particularly useful: following the naming conventions of the theory of quantum entanglement, we introduce the \textbf{(standard) robustness} \( R_{S,+}^S \) and the \textbf{generalised robustness} \( R_{S,+}^D \) \cite{29}. The latter can be equivalently expressed as
\[
R_{S,+}^D(\rho) = \inf_{\sigma \in \text{conv}(S_+)} \left\| \sigma^{-\frac{1}{2}} \rho \sigma^{-\frac{1}{2}} \right\|_{\mathcal{D}} - 1
\]
with \( \sigma^{-1} \) denoting the Moore–Penrose pseudoinverse, and is, up to logarithm, equivalent to the so-called max-relative entropy \cite{63}. We will hereafter omit the subscript in \( \mathcal{D} \) and simply use \( \geq \) to refer to the inequality with respect to the positive semidefinite cone (Löwner partial order).

By the above consideration, the standard robustness is an affine function of the base gauge \( \Gamma_{S,+ \cup (-S_+)} \), and the generalised robustness of \( \Gamma_{S,+ \cup (-\mathbb{D})} \). We recall that the effective domain of \( \Gamma_{S,+ \cup (-S_+)} \) is \( \text{span}(S_+) \), and so again we have \( \mathbb{D} \subseteq \text{dom}(R_{S,+}^S) \) only if \( \text{relint}(\text{conv}S_+) \neq \emptyset \). The domain of the generalised robustness \( R_{S,+}^D \) consists of all states supported on the subspace spanned by \( V \), i.e. \( \text{dom}(R_{S,+}^D) = S_+^{\perp \perp} \), and so \( \text{span}(V) = C^d \) is necessary and sufficient for \( R_{S,+}^D \) to be finite for all states.

We now consider the dual formulations of the gauges. Noting that \( (S_+ \cup -\mathbb{D})^o = S_+^o \cap (-\mathbb{D})^o \) and similarly for \( S_+ \cup (-S_+) \), we have
\[
R_{S,+}^D(\rho) = \frac{1}{2} \sup \left\{ \langle \rho, W' \rangle \mid W' \in S_+^o \cap (-\mathbb{D})^o \right\} - \frac{1}{2}
\]
\[
R_{S,+}^S(\rho) = \frac{1}{2} \sup \left\{ \langle \rho, W' \rangle \mid W' \in S_+^o \cap (-S_+)^o \right\} - \frac{1}{2}.
\]

With the change of variables \( W' = I - 2W \), we obtain a common representation of the Lagrange duals of the robustnesses \cite{36}:
\[
R_{S,+}^D(\rho) = \sup \left\{ -\langle \rho, W \rangle \mid W \in S_+^o \cap \mathbb{D}^o \right\}
\]
\[
R_{S,+}^S(\rho) = \sup \left\{ -\langle \rho, W \rangle \mid W \in S_+^o \cap S_+^o \right\}.
\]

It follows that strong Lagrange duality always holds for the robustness quantifiers by virtue of their being gauge functions. This will be considered in more generality in section 4.2.

We remark that, unless \( \mathcal{X} = S_+ \), the quantity \( \Gamma_{S,+ \cup (-\mathcal{X})} \) is not symmetric and thus cannot be a valid norm. A possible way to symmetrise this function is to consider the centrally symmetric set \( \mathcal{M} := (S_+ \cup (-\mathcal{X}))^o \cap ((-S_+) \cup \mathcal{X})^o \), which leads to the symmetric quantity \( \Gamma_{\mathcal{M}}(\mathcal{X}) = \max \{ \Gamma_{S,+ \cup (-\mathcal{X})}(\mathcal{X}), \Gamma_{(-S_+) \cup (\mathcal{X})} \} \).

We proceed by characterising the relation between the robustness measures and the previously introduced atomic gauges, as well as showing that the generalised robustness \( R_{S,+}^D \) always reduces to the vector atomic gauge \( \Gamma_{\mathcal{V}} \) on pure states.

\textbf{Theorem 9.} For any state \( \rho \in \text{dom}(R_{S,+}^S) \), we have
\[
\Gamma_s(\rho) - 1 \geq R_{S,+}^S(\rho).
\]
Proof. First, note that the generalised robustness can be expressed as
\[
2R_{S_+}^D(\rho) + 1 = \Gamma_{S,+}(-1)(\rho) = \sup \{ \langle \rho, W \rangle \mid W \in S_+^\circ, \langle W, \sigma \rangle \geq -1 \ \forall \sigma \in \mathbb{D} \} = 2 \sup \{ \langle \rho, W' \rangle \mid W' \in S_+^\circ, W' \in \mathbb{D}_+ \} - 1 \quad (59a)
\]
where in (59a) we make the change of variables \( W' = \frac{1}{2} (W + \mathbb{I}) \), and (59b) follows from the self-duality of the positive semidefinite cone \( \mathbb{H}_+ \) and the fact that \( \mathbb{R}_+^D = \mathbb{H}_+ \). We now have
\[
\Gamma_S(\rho) = \sup \{ \langle \rho, Z \rangle \mid Z \in S^\circ \} \geq \sup \{ \langle \rho, Z \rangle \mid Z \in \mathbb{H}_+, Z \in S^\circ \} = \sup \{ \langle \rho, Z \rangle \mid Z \in \mathbb{H}_+, |\langle a|Z|b\rangle| \leq 1 \ \forall |a\rangle, |b\rangle \in \mathcal{V} \} = \sup \{ \langle \rho, Z \rangle \mid Z \in \mathbb{H}_+, \langle a|Z|a\rangle \leq 1 \ \forall |a\rangle \in \mathcal{V} \} = \sup \{ \langle \rho, Z \rangle \mid Z \in \mathbb{H}_+, Z \in S_+^\circ \} = R_{S_+}^D(\rho) + 1
\]
where the third equality follows from lemma 8. \( \blacksquare \)

Theorem 10. For any pure state \( |\psi\rangle \langle \psi| \in \text{dom}(R_{S_+}^D) \), the generalised robustness is equivalent to the vector atomic gauge for the set \( \mathcal{V} \):
\[
R_{S_+}^D(|\psi\rangle \langle \psi|) = \Gamma_V(|\psi\rangle \langle \psi|)^2 - 1 \quad (60)
\]
Proof. The fact that we have \( R_{S_+}^D(|\psi\rangle \langle \psi|) \leq \Gamma_V(|\psi\rangle \langle \psi|)^2 - 1 \) follows from theorem 9, since by theorem 6 we have \( \Gamma_S(|\psi\rangle \langle \psi|) = \Gamma_V(|\psi\rangle \langle \psi|)^2 \) for any \( |\psi\rangle \in \text{span}(\mathcal{V}) \).

To show that \( R_{S_+}^D(|\psi\rangle \langle \psi|) \geq \Gamma_V(|\psi\rangle \langle \psi|)^2 - 1 \), from the dual characterisation of the robustness we have
\[
2R_{S_+}^D(|\psi\rangle \langle \psi|) + 1 = 2 \sup \{ \langle |\psi\rangle \langle \psi|, W' \rangle \mid W' \in S_+^\circ, W' \in \mathbb{H}_+ \} - 1 \geq 2 \sup \{ \langle |\psi\rangle \langle \psi|, |w\rangle \langle w| \rangle \mid |w\rangle \langle w| \rangle \in S_+^\circ \} - 1 = 2 \sup \{ \langle |\psi|w\rangle^2 \mid |w\rangle \langle w| \rangle \in \mathcal{V}^\circ \} - 1 = 2 \sup \{ \langle |\psi|w\rangle^2 \mid |w\rangle \in \mathcal{V}^\circ \} - 1 = 2\Gamma_V(|\psi\rangle \langle \psi|)^2 - 1. \quad (61)
\]

Proposition 11. For any state \( \rho \in \text{span}(S_+) \) we have
\[
R_{S_+}^S(\rho) \geq \Gamma_S(\rho) - 1 \quad (62)
\]
Proof. First, recall that by theorems 6 and 10 we have \( R_{S_+}^S(|\psi\rangle \langle \psi|) \geq R_{S_+}^D(|\psi\rangle \langle \psi|) = \Gamma_S(|\psi\rangle \langle \psi|) - 1 \) for any \( |\psi\rangle \langle \psi| \in \text{dom}(R_{S_+}^D) \). Together with the fact that
Proposition 12. For any state $\rho \in \text{dom}(R_{S_+}^2)$ it holds that

$$R_{S_+}^2(\rho) \geq \frac{\text{Tr}(\rho^2)}{\Gamma_{S_+}(\rho)} - 1.$$  

Proof. First, notice that we do not need to assume $\Gamma_{S_+}(\rho) \neq 0$, since any positive semidefinite $\rho \in \text{dom}(R_{S_+}^2)$ satisfies $\text{supp}(\rho) \subseteq \text{span}(V)$ and so we cannot have that $\langle \rho, \sigma \rangle = 0 \forall \sigma \in S_+$. From $\Gamma_{S_+} = \gamma_{S_+}^2$, we then have that $\frac{\rho}{\Gamma_{S_+}(\rho)} \in S_+$. Since $\rho \in H_+$, this is then a feasible solution to the dual formulation of the generalised robustness (equation (59)) and so we have

$$R_{S_+}^2(\rho) \geq \left(\rho, \frac{\rho}{\Gamma_{S_+}(\rho)} \right) - 1$$

as required.

We remark that the above bound constitutes an improvement over the bound one can obtain from the Cauchy–Schwarz inequality for $\Gamma_{S_+ \cup (-D)}$, namely $R_{S_+}^2(\rho) \geq \frac{1}{2} \left(\frac{\text{Tr}(\rho^2)}{\Gamma_{S_+}(\rho)} - 1\right)$.

Proposition 13. For any $P \in H_+$ it holds that

$$\Gamma_{S_+ \cup (-D)}(P) = \Gamma_{S_+}(P).$$
Proof. By the positive semidefiniteness of $P$ we have
\[
\Gamma^{\circ}_{\mathbb{S}_+ \cup \{-D\}}(P) = \sup \{ \langle P, Z \rangle \mid Z \in \text{conv} (\mathbb{S}_+ \cup \{-D\}) \} \\
= \max \{ 0, \sup \{ \langle P, Z \rangle \mid Z \in \mathbb{S}_+ \} \} \\
= \sup \{ \langle P, Z \rangle \mid Z \in \mathbb{S}_+ \} \\
= \Gamma^{\circ}_{\mathbb{S}_+}(P).
\] (68)

4. Atomic gauges as resource quantifiers

A full characterisation of a resource theory requires, in addition to the chosen set of free states without a given resource, the choice of a relevant set of free operations which cannot generate a given resource [17]. For simplicity, in the following we will limit ourselves to the discussion of quantum operations acting as linear operators on the vector space of $d \times d$-dimensional Hermitian matrices $\mathbb{H}$; the results can be generalised to maps between different vector spaces by suitably defining the set of free states in the input space as well as the set of free states in the output space (see e.g. [20]).

The definition of what exactly constitutes the free operations is frequently dependent on the resource theory or the physical setting under consideration. The largest possible set of free operations are the resource non-generating operations $\mathcal{O}_{\text{RNG}}$, such that for any $\Phi \in \mathcal{O}_{\text{RNG}}$ we have $\sigma \in \mathbb{S}_+^* \Rightarrow \Phi(\sigma) \in \mathbb{S}_+^*$. In particular, a trace-preserving resource non-generating operation acting on a free state always results in another free state. Often, a smaller subset of operations is considered: they are the resource-free operations $\mathcal{O}_{\text{RF}}$, consisting of operations $\Lambda$ which admit a Kraus decomposition of the form $\Lambda(\rho) = \sum_{i} K_{\rho} \sigma K_{\rho}^\dagger$ such that $\sigma \in \mathbb{S}_+^* \Rightarrow K_{\rho} \sigma K_{\rho}^\dagger \in \mathbb{S}_+^* \forall n$. The physical motivation for the choice of resource-free operations is that it guarantees that no resource can be created from a non-resource state in any possible measurement outcome. In the theory of entanglement, these are the separable operations [65], while in the theory of coherence they are called incoherent operations [7]. Even these operations are often considered to not reflect the physical restrictions sufficiently well, and much smaller subsets of physically relevant operations are used; for instance, in entanglement theory the set of operations of interest are the local operations and classical communication (LOCC) [66, 67], and in coherence theory a common choice are the strictly incoherent operations [68] or even smaller subsets [69–71].

Identifying $\text{conv}(\mathbb{S}_+)$ with the set of free states and $\mathcal{O}$ with a chosen set of free operations, we define a valid measure for the given resource to be a function $M : \mathbb{D} \rightarrow \mathbb{R}_+ \cup \{\infty\}$ which satisfies two basic criteria:

1. Faithfulness: $M(\rho) = 0$ if and only if $\rho \in \text{conv}(\mathbb{S}_+)$.  
2. Monotonicity: $M(\Theta(\rho)) \leq M(\rho)$ for all completely positive trace-preserving (CPTP) operations $\Theta \in \mathcal{O}$.

Often, additional conditions are imposed, the two most common ones being:

1. Convexity: $M \left( \sum_{i} t_i \rho_i \right) \leq \sum_{i} t_i M(\rho_i)$ for $t_i \in \mathbb{R}_+, \rho_i \in \mathbb{D}, \sum_i t_i = 1$.  
2. Strong monotonicity: $\sum_{i} p_i M \left( \frac{\Theta_i(\rho)}{p_i} \right) \leq M(\rho)$ with $p_i = \text{Tr} \Theta_i(\rho)$, where $\Theta_i \in \mathcal{O}$ are completely positive operations such that $\sum_i \Theta_i$ is trace preserving.

The choice of the free operations of interest $\mathcal{O}$ will, in general, not be unique—however, we stress that (strong) monotonicity under a given class of operations implies (strong) monotonicity under any subset of this class, and so it suffices to investigate monotonicity under...
larger sets of operations. Further, note that strong monotonicity implies monotonicity, which is not true for a slightly weaker notion of strong monotonicity common in the literature (see e.g. [7, 72, 73]), which corresponds in the present notation to identifying each $\Theta_i$ with a single resource non-generating Kraus operator, i.e. $\Theta_i(\rho) = K_i \rho K_i^\dagger$ [23].

4.1. Properties of atomic gauges

We now verify the criteria for the candidate measures: $\Gamma_S(\rho) - 1$, $\Gamma_{S_+}^{U}(\rho) - 1$, $R_S^S_+ (\rho)$, and $R_S^D_+ (\rho)$. Note that, when applying the functions to a given resource theory, considerations have to be made about their effective domains (see sections 3.1 and 3.2).

**Theorem 14.** A state $\rho \in \mathcal{D}$ belongs to the set $\text{conv}(S_+)$ if and only if

$$\Gamma_{S_+}(\rho) - 1 = \Gamma_S(\rho) - 1 = \Gamma_{S_+}(\rho(-S_+)) - 1 = \Gamma_S^{D_+}(\rho) - 1 = R_S^S_+(\rho) = R_S^D_+(\rho) = 0.$$  

(69)

That is, all of the considered measures are faithful.

**Proof.** It is helpful to recall that the gauge function of the set

$$U = \{ |x\rangle\langle y| \mid \langle x|y\rangle \leq 1, \langle y|y\rangle \leq 1 \}$$  

is just the trace norm $\|\cdot\|_1$. Since $S_+ \subset S_+ \cup (-S_+) \subset S \subset U$, $S_+ \subset S^{D_+} \subset U$, and $S_+ \subset S_+ \cup (-\mathcal{D}) \subset U$ it follows that $\Gamma_U$ minorises all of the considered gauges, and so each of the gauges cannot be smaller than 1 when $\rho \in \mathcal{D}$ because $\|\rho\|_1 = 1$.

Then if $\rho \in \text{conv}(S_+)$, we have $\Gamma_{S_+}(\rho) = 1$ by definition, and all the other gauges also have to be equal to 1 because they are majorised by $\Gamma_{S_+}$ (equation (33)), which in turn means the robustnesses will be zero.

Conversely, assume that $R_S^S_+(\rho) = 0$, which means that $\Gamma_{S_+}(\rho(-S_+)) = 1$. This gives that $\rho \in \text{conv}(S_+ \cup (-\mathcal{D}))$, but since $\rho \in \mathcal{D}$ by assumption and $\text{conv}(S_+ \cup (-\mathcal{D})) \cap \mathcal{D} = \text{conv}(S_+)$, we necessarily have $\rho \in \text{conv}(S_+)$. Noting by theorem 9 and the inequalities between the gauges that $R_S^S_+(\rho) + 1$ minorises all other gauges in consideration, it follows that any of the gauges being equal to 1 implies that $R_S^S_+$ is zero, proving the claim. ■

**Proposition 15.** All of the considered measures are convex.

**Proof.** Every gauge function of a convex set is convex. ■

**Lemma 16.** Let $C$ denote either $\text{conv}(S_+ \cup (-S_+))$ or $\text{conv}(S_+ \cup (-\mathcal{D}))$. Then, given a resource non-generating completely positive map $\Phi \in \mathcal{O}_{\text{RNG}}$ and an operator $X$, we have $X \in C \Rightarrow \Phi(X) \in \mathbb{R}^+ C$.

**Proof.** For $C = \text{conv}(S_+ \cup (-S_+))$, write $X = s\sigma^+ - (1-s)\sigma^-$ with $\sigma^\pm \in \text{conv}(S_+)$, $s \in [0,1]$. Then $\Phi(X) = s\Phi(\sigma^+) - (1-s)\Phi(\sigma^-) = s\text{Tr}(\Phi(\sigma^+))\varsigma^+ + (1-s)\text{Tr}(\Phi(\sigma^-))\varsigma^-$ for some $\varsigma^\pm \in \text{conv}(S_+)$ by linearity and the resource non-generating property of $\Phi$. We then have $\Phi(X) = \text{Tr}(\Phi(X))(s\varsigma^+ - (1-s)\varsigma^-)$ as required.

For $C = \text{conv}(S_+ \cup (-\mathcal{D}))$, write $X = s\sigma - (1-s)\pi$ with $\sigma \in \text{conv}(S_+)$, $\pi \in \mathcal{D}$, $s \in [0,1]$. Then $\Phi(X) = s\Phi(\sigma) - (1-s)\Phi(\pi) = s\text{Tr}(\Phi(\sigma))\varsigma - (1-s)\text{Tr}(\Phi(\pi))\varsigma$ with $\varsigma \in \text{conv}(S_+)$ by linearity and the resource non-generating property of $\Phi$, and $\varsigma \in \mathcal{D}$ as $\Phi$ is completely positive. This gives $\Phi(X) = \text{Tr}(\Phi(X))(s\varsigma - (1-s)\varsigma)$ as required. ■
Lemma 17. Let $\mathcal{C}$ denote either $\text{conv}(S_+)$ or $\text{conv}(S^\perp_+).$ Then, given a resource-free completely positive map $\Lambda \in \mathcal{O}_{\text{RF}}$ and an operator $X$, we have $X \in \mathcal{C} \Rightarrow \Lambda(X) \in \mathbb{R}^+_C.$

Proof. Let us consider $\mathcal{C} = \text{conv}(S)$ first. Write any $\Lambda \in \mathcal{O}_{\text{RF}}$ in its Kraus decomposition as $\Lambda(\rho) = \sum_n K_n \rho K_n^\dagger.$ By definition of the resource-free operations, we can note that for every pure state $|v_i\rangle \in \mathcal{V}$, we have $K_n|v_i\rangle = |v'_{ni}\rangle$ for some $|v'_{ni}\rangle \in \mathbb{R}^+_V$ as the complex phase can be absorbed into the state $|v'_{ni}\rangle.$ By definition, any operator $X \in \text{conv}(S)$ can be written as $X = \sum_i c_i |v_i\rangle \langle u_i|$ for some coefficients $c_i \in \mathbb{R}^+$ with $\sum_i c_i = 1$ and states $|v_i\rangle \in \mathcal{V}$, $|u_i\rangle \in \mathcal{V}$, which then gives

$$\Lambda(X) = \sum_n K_n \left( \sum_i c_i |v_i\rangle \langle u_i| \right) K_n^\dagger,$$

which is explicitly in $S^{**}.$

Take now $\text{conv}(S^\perp_+).$ Noting that any state in $\text{conv}(S^\perp_+)$ can be written as $\rho = \sum_i c_i |w_i\rangle \langle w_i|$ with $|w_i\rangle \in \text{conv}(\mathcal{V})$, $c_i \in \mathbb{R}^+$, and $\sum_i c_i = 1$, and similarly each $|w_i\rangle$ can be written as $|w_i\rangle = \sum_j d_{ij} |v_{ij}\rangle$ with $|v_{ij}\rangle \in \mathcal{V}$, $d_{ij} \in \mathbb{R}^+$, $\sum_j d_{ij} = 1$. This then gives

$$\Lambda(\rho) = \sum_n K_n \left( \sum_{i,j,k} c_i d_{ij} d_{ik} |v_{ij}\rangle \langle v_{ik}| \right) K_n^\dagger,$$

where

$$|q_i\rangle = \sum_{j,n} d_{ij} |v'_{nj}\rangle.$$  

(73)

Since each $|q_i\rangle \in \mathcal{V}^{**}$, we have that $\Lambda(\rho) \in S^{**}_{+}$ as required. ■

Theorem 18. The robustness measures $R^{\mathcal{D}}_{S_+}$ and $R^{\mathcal{D}_{S_+}}_{S_+}$ satisfy strong monotonicity under resource non-generating maps $\mathcal{O}_{\text{RNG}}.$

Theorem 19. The atomic gauges $\Gamma_{\mathcal{S}}$ and $\Gamma_{\mathcal{S}^\perp_+}$ satisfy strong monotonicity under resource-free maps $\mathcal{O}_{\text{RF}}.$

Proof. Let $\mathcal{C}$ denote one of the sets: $(S_+ \cup (-S_+))$, $(S_+ \cup (-D))$, $\mathcal{S}$, or $S^\perp_{+}$. Depending on the choice of the set, let $\mathcal{O}$ denote the relevant set of free operations—$\mathcal{O}_{\text{RNG}}$ or $\mathcal{O}_{\text{RF}}$. Now, let $\Theta = \sum \Phi \in \mathcal{O}$ denote a free CPTP map, where each $\Phi \in \mathcal{O}$ is a trace non-increasing, completely positive map.
By definition of the atomic gauge $\Gamma_C$, for any $\rho \in \text{dom}(\Gamma_C) \cap \mathbb{D}$ we have that

$$\frac{\rho}{\Gamma_C(\rho)} = X \in \text{conv}(C).$$

(74)

Then

$$\Phi(\rho) = \Phi_i(\Gamma_C(\rho) X) = \Gamma_C(\rho) \Phi(X) = \Gamma_C(\rho) Y_i$$

(75)

for some $Y_i \in \text{Tr}Y_i \text{conv}(C)$ by lemmas 16 or 17. Now let $p_i = \text{Tr}(\Phi_i(\rho))$. Dividing equation (75) by $p_i$, we have that

$$\frac{\Phi_i(\rho)}{p_i} = \frac{\Gamma_C(\rho) \text{Tr}Y_i}{p_i} \in \text{conv}(C)$$

(76)

and hence $\frac{\Gamma_C(\rho) \text{Tr}Y_i}{p_i}$ is a feasible solution to $\Gamma_C \left( \frac{\Phi_i(\rho)}{p_i} \right) = \inf \left\{ \lambda \in \mathbb{R}_+ \mid \frac{\Phi_i(\rho)}{p_i} \in \lambda \text{conv}(C) \right\}$, that is,

$$\Gamma_C \left( \frac{\Phi_i(\rho)}{p_i} \right) \leq \frac{\Gamma_C(\rho) \text{Tr}Y_i}{p_i}.$$  

(77)

Notice now that, since $\Gamma_C(\rho) \geq 1$ and $\sum_i \Phi_i$ is trace preserving, we have $1 = \text{Tr}\rho \geq \text{Tr}X = \text{Tr} \sum_i Y_i$, which then gives

$$\sum_i p_i \Gamma_C \left( \frac{\Phi_i(\rho)}{p_i} \right) \leq \Gamma_C(\rho) \sum_i \text{Tr}Y_i \leq \Gamma_C(\rho)$$

(78)

and so strong monotonicity is satisfied.  

In fact, although the choice of the four measures $\Gamma_S$, $\Gamma_S^-$, $R_{S^+}$ and $R_{S^+}$ is somewhat natural in the framework of the gauge functions, there is of course no reason to limit oneself to these particular measures and the two types of free operations that we have considered. One can establish a similar sufficient condition for other gauge-based measures:

**Theorem 20.** Let $\Gamma_C$ be the atomic gauge function corresponding to a compact set $C$. Let $\mathcal{O}$ denote a chosen set of free operations. We then have that if the convex cone $C^{**}$ is closed under the operations $\mathcal{O}$, i.e. $\sigma \in C^{**} \Rightarrow \Theta(\sigma) \in C^{**}$ for all $\Theta \in \mathcal{O}$, then $\Gamma_C$ is strongly monotonic under $\mathcal{O}$.

The proof is the same as above.

**Remark.** Instead of choosing the resource quantifier as $M = \Gamma_C - 1$ for one of the gauge functions $\Gamma_C$, one can instead consider $M = f \circ \Gamma_C$ for any monotonically non-decreasing function $f$ on the interval $[1, \infty)$ s.t. $f(1) = 0$. Any choice of a convex $f$ then preserves the convexity of the measure, and any choice of a concave $f$ preserves the strong monotonicity—a common choice of a concave function is $f = \log_2$, leading to operationally useful monotones [28, 74, 75].
4.2. Dual characterisation and resource witnesses

In quantum resource theories, elements of the dual cone $S_+^*$ are often called witnesses of the given resource. The notion of witnesses is a fundamental concept that found a variety of uses in the characterisation, detection, and quantification of quantum resources [36, 76–78].

The set of witnesses can also be described in terms of the polar set $S_+^*$—the equivalence is made explicit by noting that a witness can be obtained from any $S \in S_+^*$ simply by considering $I - S \in S_+^*$. This gives an intuitive interpretation of the polar gauge in this sense:

**Proposition 21.** For any $X \in \mathbb{H}$ it holds that

$$\Gamma_{S_+}(X) = \inf \{ \lambda \in \mathbb{R}_+ \mid \lambda I - X \in S_+^* \}. \quad (79)$$

**Proof.** Recalling that $\Gamma_{S_+} = \Gamma_{S^*_+} = \gamma_{S^*_+}$, we have $\Gamma_{S_+}(X) = \inf \{ \lambda \in \mathbb{R}_+ \mid X \in \lambda S_+^* \}$ and the result follows since $(I, \sigma) = 1 \forall \sigma \in S_+$. ■

**Remark.** Notice that if $X$ is such that $\langle \sigma, X \rangle \leq 0 \forall \sigma \in S_+$, then $\Gamma_{S_+}(X) = 0$. In particular, a positive semidefinite matrix can have $\Gamma_{S_+}(X) = 0$ if and only if $X \in S_+^{\perp}$, where $S_+^{\perp} = S_+^* \cap (-S_+)^*$ is the orthogonal complement of $S_+$. Note that $S_+^{\perp} \cap \mathbb{H}^d = \{0\}$ when span($\mathcal{V}$) = $\mathbb{C}^d$.

The crucial property of witnesses applied to quantum resources is that, since conv$(S_+)$ is a convex and closed set, by the strongly separating hyperplane theorem [26, 11.4] for every $\rho \notin$ conv$(S_+)$ there exists a witness $W \in S_+^*$ such that $\langle \rho, W \rangle < 0$, thus detecting a given resource. On the other hand, if $\rho \in$ conv$(S_+)$, then we necessarily have $\langle \rho, W \rangle \geq 0 \forall W \in S_+^*$.

This leads to a natural formalism of witness-based measures, quantifying how much a given state can violate the condition $\langle \rho, W \rangle \geq 0$: one constructs a general witness-based measure as [36]

$$V^C_{S_+}(\rho) = \sup \{ -\langle \rho, W \rangle \mid W \in S_+^* \cap \mathcal{C} \} \quad (80)$$

where $\mathcal{C}$ is a set representing some additional constraints on the set of witnesses under consideration. This approach is particularly useful in experimental settings, allowing for the detection and quantification of resources without the need for full state tomography [37, 38].

All of the gauge functions considered in this work can be written in this form with a suitable choice of $\mathcal{C}$ (up to a constant), which can be seen from their dual representation. For example, the standard robustness corresponds to $V_{S_+}^C$ with the choice $\mathcal{C} = S_+^*$, and the generalised robustness to $\mathcal{C} = \mathbb{D}^0 = \{ X \mid X \preceq I \}$. More generally, we can establish the following equivalence:

**Proposition 22.** Let $\mathcal{U} = \{ X \in \mathbb{H} \mid \langle I, X \rangle = 1 \}$. If $\mathcal{C}$ can be expressed as $\mathcal{C} = \mathcal{X}^\circ$ for some subset $\mathcal{X} \subseteq \mathcal{U}$, then

$$V_{S_+}^\mathcal{C}(\rho) = \frac{1}{2} \langle \Gamma_{S_+ \cup (-\mathcal{X})}(\rho) - 1 \rangle \quad (81)$$

for any $\rho \in \mathbb{D}$. Likewise, if $\mathcal{C} = \mathcal{Y}^\circ$ for some $\mathcal{Y} \subseteq -\mathcal{U}$, then

$$V_{S_+}^\mathcal{C}(\rho) = \langle \Gamma_{S_+ \cup (-\mathcal{Y})}(\rho) - 1 \rangle. \quad (82)$$

**Proof.** Take the standard expression for the witness-based measure in equation (80) and apply the change of variables $W' = I - 2W$ in the case of $\mathcal{X}$, or $W' = I - W$ in the case of $\mathcal{Y}$.

The result then follows from the dual characterisation of the gauge functions. ■
One can note a similarity of the above forms to the generalised base gauges considered in section 3.2.

In the cases considered in proposition 22, strong Lagrange duality always holds by virtue of the dual representation of atomic gauges. For more general sets \( C \) one can note that since \( S_+ \) is bounded, we have \( 0 \in \text{int}(S_+) \) [26, 14.5.1], and it follows that \( I \in \text{int}(S_+) \). This fact is useful in showing that strong Lagrange duality holds for a given measure—by Slater’s condition [51], strong duality holds if there exists a witness \( W \in \text{relint}(S_+ \cap C) \). It is then sufficient to show the existence of a witness in \( \text{relint}(C) \) which is in the neighbourhood of \( I \).

An example of a witness-based measure is obtained by taking \( V_{S_+}^{C} \) with \( C = \{ X | \langle 1, X \rangle \leq d \} \) [79]. Noting that this corresponds to \( C = X^\circ \) with \( X = \{ \frac{1}{d} \} \), we obtain

\[
V_{S_+}^{C} (\rho) = R_{S_+}^{(\frac{1}{d})} (\rho) = \inf \left\{ s \in \mathbb{R}_+ \mid \rho + \frac{s}{d} \in S_+^\circ \right\}
\]

which defines the random robustness [29]. Random robustness has full domain iff \( \frac{1}{d} \in \text{relint} (S_+) \), and it corresponds to the gauge function \( \frac{1}{d} (\Gamma_{S_+ \cup \{ -\frac{1}{d} \}} - 1) \). Alternatively, one can think of it as the atomic gauge function of \( S_+ \) under a reparametrisation such that \( \frac{1}{d} \) is the origin. Note that the random robustness is not a monotone under the general free operations \( \mathcal{O}_{\text{RNG}} \), but by theorem 20 it can be noted to be faithful and strongly monotonic under unital resource non-generating operations (i.e. \( \Gamma \in \mathcal{O}_{\text{RNG}} \) such that \( \Gamma (I) = I \)). By the set inclusion of the corresponding unit balls we get \( R_{S_+}^{(\frac{1}{d})} (\rho) \geq R_{S_+}^{\frac{1}{d}} (\rho) \).

Another common choice is to consider \( V_{S}^{C} \) with \( C = (\mathbb{D})^\circ = \{ X | X \succeq -1 \} \), which by strong Lagrange duality is equal to the so-called best free approximation BFA, generalising the best separable approximation [80]:

\[
\text{BFA}_{S_+} (\rho) = 1 - \sup \left\{ \lambda \in \mathbb{R}_+ \mid \rho = \lambda \sigma + (1 - \lambda) \omega, \sigma \in \text{conv}(S_+), \omega \in \mathbb{D} \right\}.
\]

This expression is then equivalent to the gauge function \( \Gamma_{S_+ \cup \{ \frac{1}{d} \}} - 1 \). Noting that the cone generated by the set \( S_+ \cup \{ \frac{1}{d} \} \) is closed under resource non-generating operations, we have that the best free approximation is a faithful strong monotone under \( \mathcal{O}_{\text{RNG}} \) by theorem 20.

### 4.3. Relations with distance-based measures

One can define a faithful quantifier of any resource simply by considering the distance to the set of free states. That is, we can define

\[
D_{S_+} (\rho) = \inf_{\sigma \in \text{conv}(S_+)} D(\rho, \sigma)
\]

for some quasi-metric \( D \) contractive under completely positive trace-preserving maps [66, 81]. Any such measure is then a (weak) monotone under resource non-generating operations. Although the representation is appealing from an intuitive point of view, the measures defined in this way are frequently difficult to evaluate and investigate in practice, and few results about their properties such as strong monotonicity are known.

The distance-based quantifiers do not fit into the gauge function formalism directly, but we can nevertheless obtain relations between the gauge-based and distance-based measures in several cases—we will consider some representative examples of such quantifiers.
4.3.1. Trace distance and other gauge-based distances. A commonly encountered case is when \( D \) is itself based on a gauge function—this includes, for instance, the fundamental measure of trace distance \( D_{S_+}(\rho) \) which is obtained for \( D(\rho, \sigma) = \| \rho - \sigma \|_1 \). In general, one can consider

\[
D_{S_+}(\rho) = \inf_{\sigma \in \text{conv}(S_+)} \Gamma_C(\rho - \sigma)
\]

for some set \( C \) s.t. \( \mathbb{H} \subseteq \text{span}(C) \). We will take \( C \subseteq \mathbb{H} \) for simplicity, but the same considerations apply to more general sets of complex matrices with the inner product \( \langle \cdot, \cdot \rangle \). To see the difference between the distance-based measures and gauge functions, we can consider the dual form of the general quantifier \( D_{S_+} \):

\[
D_{S_+}(\rho) = \inf_{\sigma \in \text{conv}(S_+)} \sup_{W \in C^\circ} \langle W, \rho - \sigma \rangle
\]

which follows by Sion’s minimax theorem [82] (or can be equivalently derived by considering the Lagrange dual of the original problem explicitly). We emphasise that the function \( \mu_{S_+}(W) := \sup_{\sigma \in S_+} \langle W, \sigma \rangle \) is, in general, different from the polar gauge \( \Gamma_{S_+}^\circ(W) = \max \{ 0, \mu_{S_+}(W) \} \). This representation can nevertheless be helpful since the polar gauges, and as a result the function \( \mu_{S_+} \), are often easier to characterise (see e.g. section 5).

As an explicit example, consider the trace distance \( T_{S_+}(\rho) \), which is obtained for \( C = \{ X \mid \| X \|_1 \leq 1 \} \) and thus gives

\[
T_{S_+}(\rho) = \sup \left\{ \Re \langle W, \rho \rangle - \mu_{S_+}(W) \mid \| W \|_\infty \leq 1 \right\}. \tag{88}
\]

An alternative formulation of the trace distance can be obtained by noting that the trace norm \( \| \cdot \|_1 \) admits a representation as the base norm \( \Gamma_{D_+(-D)} \) in the space of Hermitian matrices, that is, for a Hermitian matrix it suffices to optimise over Hermitian \( W \). Since any \( \rho - \sigma \) is Hermitian, we can write

\[
T_{S_+}(\rho) = \inf_{\sigma \in \text{conv}(S_+)} \sup \left\{ \langle W, \rho - \sigma \rangle \mid W \in D^\circ \cap (-D)^\circ \right\}
\]

\[
= \inf_{\sigma \in \text{conv}(S_+)} \sup \left\{ \langle W', \rho - \sigma \rangle - \langle \mathbb{1}, \rho \rangle + \langle \mathbb{1}, \sigma \rangle \mid W' \in \left( \frac{1}{2} D^\circ \right)^\circ \cap D^\circ \right\}
\]

\[
= 2 \sup \left\{ \langle W', \rho \rangle - \Gamma_{S_+}^\circ(W') \mid \mathbb{1} \succeq W' \succeq 0 \right\}. \tag{89}
\]

where in the second line we make the change of variables \( W' = W + \mathbb{1} \), and the last equality follows because \( \mu_{S_+}(W') = \Gamma_{S_+}^\circ(W') \) for any \( W' \in D^\circ \cap H_+ \). The above representation can be used to relate the trace distance to the gauge-based quantifiers: by noting the fact that \( D^\circ \subseteq S_+^\circ \) and the non-negativity of the polar gauge \( \Gamma^\circ \), we obtain

\[
T_{S_+}(\rho) \leq 2 \sup \left\{ \langle W', \rho \rangle - \Gamma_{S_+}^\circ(W') \mid W' \in S_+^\circ \cap H_+ \right\}
\]

\[
\leq 2 \sup \left\{ \langle W', \rho \rangle \mid W' \in S_+^\circ \cap H_+ \right\}
\]

\[
= 2 \mathcal{R}_{S_+}(\rho). \tag{90}
\]

Additionally, for any \( \rho \) s.t. \( R^D_{S_+}(\rho) \leq \frac{1}{2} \), we can use the Cauchy–Schwarz inequality for \( \Gamma_{D_+(-D)} \) along with proposition 13 to further tighten the inequality to \( T_{S_+}(\rho) \leq R^D_{S_+}(\rho) \).
4.3.2. Geometric measures. The family of geometric measures with respect to $\mathcal{S}_+$ is defined by noting that, for pure states, the quantity $\Gamma^\psi_\mathcal{S}_+ (|\psi\rangle)$ effectively quantifies the resource contained in a state by measuring the largest possible overlap with a free state [83, 84], reaching its maximal value 1 only on the set of free states. One can then take some monotonically non-increasing function $f$ such that $f(1) = 0$ to define a measure $f \circ \Gamma^\psi_\mathcal{S}_+$, which can be extended through the convex roof to mixed states. One of the most common variants of the measure is then given by

$$G_{\mathcal{S}_+} (\rho) := \left(1 - \Gamma^\psi_\mathcal{S}_+ \right) (\rho) = 1 - \Gamma^{\mathcal{S}_+}_\mathcal{S}_+ (\rho)$$

$$= 1 - \sup \left\{ \sum_i p_i \Gamma^\psi_i (|\psi_i\rangle)^2 \right\} \quad \rho = \sum_i p_i |\psi_i\rangle \langle \psi_i|, \ p_i \in \mathbb{R}_+, \ \sum_i p_i = 1 \right\} .$$  \hfill (91)

It is related to the distance-based measure based on the quantum fidelity $F(\rho, \sigma) = \|\sqrt{\rho} \sqrt{\sigma} \|_1^2$, given by

$$G'_{\mathcal{S}_+} (\rho) := \inf_{\sigma \in \text{conv}(\mathcal{S}_+)} \left(1 - \|\sqrt{\rho} \sqrt{\sigma} \|_1^2 \right) = \inf_{\sigma \in \text{conv}(\mathcal{S}_+)} \left(1 - \text{Tr} \left(\sqrt{\rho C} \sqrt{\rho} \right)^2 \right) ,$$  \hfill (92)

and in fact, the following result holds:

**Proposition 23 (Streltsov et al [85]).** The geometric measure $G_{\mathcal{S}_+}$ and the fidelity-based distance measure $G'_{\mathcal{S}_+}$ are equal. That is,

$$\Gamma^{\mathcal{S}_+}_\mathcal{S}_+ (\rho) = \sup_{\sigma \in \text{conv}(\mathcal{S}_+)} \|\sqrt{\rho} \sqrt{\sigma} \|_1^2 .$$  \hfill (93)

The proof, applied to any set $\mathcal{S}_+$ in the present formalism, follows straightforwardly from [85] (see e.g. [86]). The result is remarkable in that it reduces the quantification of the convex roof–based measure $G_{\mathcal{S}_+}$ to a convex optimisation problem.

$\Gamma^{\mathcal{S}_+}_\mathcal{S}_+$ is concave and therefore is larger on $\mathbb{D}$ than any convex function equal to it on the extremal points of the set, including in particular the gauge $\Gamma^{\mathcal{S}_+}_\mathcal{S}_+$ itself. Noting the equivalence between dual gauges (propositions 7 and 13), we thus obtain the bound

$$G_{\mathcal{S}_+} (\rho) \leq 1 - \Gamma^{\mathcal{S}_+}_{\mathcal{S}_+} (\rho) = 1 - \Gamma^{\mathcal{S}_+}_{\mathcal{S}_+ \cup (-\mathcal{S}_+)} (\rho) = 1 - \Gamma^{\mathcal{S}_+}_\mathcal{S}_+ (1 - \Gamma^{\mathcal{S}_+}_{\mathcal{S}_+ \cup (-\mathcal{D}}) (\rho) \right) \right) .$$  \hfill (94)

which holds for any density matrix $\rho$. From proposition 12 we then have that

$$R^{\mathcal{D}}_{\mathcal{S}_+} (\rho) \geq \frac{\text{Tr}(\rho^2)}{\Gamma^{\mathcal{S}_+}_\mathcal{S}_+ (\rho)} - 1 \geq \frac{\text{Tr}(\rho^2)}{1 - G_{\mathcal{S}_+} (\rho)} - 1 .$$  \hfill (95)

for any $\rho \in \text{dom}(R^{\mathcal{D}}_{\mathcal{S}_+})$. This in particular establishes the relation

$$R^{\mathcal{D}}_{\mathcal{S}_+} (|\psi\rangle \langle \psi|) \geq \frac{1}{1 - G_{\mathcal{S}_+} (|\psi\rangle \langle \psi|)} - 1 = \frac{G_{\mathcal{S}_+} (|\psi\rangle \langle \psi|)}{1 - G_{\mathcal{S}_+} (|\psi\rangle \langle \psi|)}$$  \hfill (96)

for all $|\psi\rangle \in \text{span}(\mathcal{V})$, which generalises a known property of the robustness of entanglement [87].
4.3.3. Relative entropy. Let $S(\rho\|\sigma)$ denote the quantum relative entropy, defined as

\[
S(\rho\|\sigma) = \begin{cases} 
\text{Tr} (\rho \log_2 \rho - \rho \log_2 \sigma) & \text{if } \text{supp}(\rho) \subseteq \text{supp}(\sigma), \\
\infty & \text{otherwise}.
\end{cases}
\]

with \(\text{supp}(\rho)\) denoting the support of an operator. This quantity is neither symmetric nor subadditive, but it nevertheless can be treated as a quasi-metric and used as a measure to faithfully quantify a given quantum resource [66, 81]. A quantifier of interest is then the relative entropy with respect to \(S_+\),

\[
S_{S_+}(\rho) = \inf_{\sigma \in \text{conv}(S_+)} S(\rho\|\sigma).
\]

Note that \(\text{dom}(S_{S_+}) = \text{dom}(R_{S_+}^\sigma)\).

One can obtain useful relations between this quantity and atomic gauges, generalising results for entanglement and coherence theories found e.g. in [63, 75]. The connection between the two frameworks is made through quantities called the max- and min-relative entropy, defined as [63, 88]

\[
S_{\text{max}}(\rho\|\sigma) = \inf \{ s \in \mathbb{R}_+ \mid \rho \preceq 2^s \sigma \} = \log_2 \inf \{ s \in \mathbb{R}_+ \mid \rho \preceq s \sigma \}
\]

\[
S_{\text{min}}(\rho\|\sigma) = -\log_2 (\Pi_{\rho}, \sigma)
\]

where \(\Pi_{\rho}\) denotes the orthogonal projection onto \(\text{supp}(\rho)\). From the definition of the generalised robustness \(R_{S_+}^\sigma\), it then follows that

\[
\inf_{\sigma \in \text{conv}(S_+)} S_{\text{max}}(\rho\|\sigma) = \log_2 \left( 1 + R_{S_+}^\sigma(\rho) \right),
\]

and by the positive semidefiniteness of \(\Pi_{\rho}\) as well as the monotonicity of the logarithm we have

\[
\inf_{\sigma \in \text{conv}(S_+)} S_{\text{min}}(\rho\|\sigma) = -\log_2 \Gamma_{S_+}^\sigma(\Pi_{\rho}).
\]

Using the relation \(S_{\text{min}}(\rho\|\sigma) \leq S(\rho\|\sigma) \leq S_{\text{max}}(\rho\|\sigma)\) [63], we then have

\[
-\log_2 \Gamma_{S_+}^\sigma(\Pi_{\rho}) \leq S_{S_+}(\rho) \leq \log_2 \left( 1 + R_{S_+}^\sigma(\rho) \right) \leq \log_2 \Gamma_{G}(\rho)
\]

where the third inequality follows from theorem 9. This establishes a quantitative relation between the non-convex gauge-based strong monotones and the relative entropy. In the resource theory of quantum coherence, it has been conjectured that the stronger inequality \(S_{S_+}(\rho) \leq \Gamma_{G}(\rho) - 1\) holds [75, 89]. Following [75], we can use the fact that \(x \geq \log_2(1+x)\) \(\forall x \geq 1\) to similarly establish

\[
S_{S_+}(\rho) \leq R_{S_+}^\sigma(\rho) \leq \Gamma_{G}(\rho) - 1 \quad \forall \rho \text{ s.t. } R_{S_+}^\sigma(\rho) \geq 1
\]

\[
S_{S_+}(\rho) \leq R_{S_+}^\sigma(\rho) \log_2 e \leq (\Gamma_{G}(\rho) - 1) \log_2 e \quad \forall \rho,
\]

which suggests that the conjecture can be extended to more general resource theories. We remark that, by proposition 12, a sufficient condition for \(R_{S_+}^\sigma(\rho) \geq 1\) to hold is \(\Gamma_{S_+}^\sigma(\rho) \leq \frac{1}{2} \text{Tr}(\rho^2)\).

5. Applications

We now show how to apply the formalism introduced in the previous sections to two representative quantum resources—entanglement and coherence—as well as the recently established
resource theory of magic states, demonstrating the universality of the results obtained in this work. We introduce new gauge-based quantifiers as well as show that many known measures of the three resources fit into the gauge function framework, allowing for their characterisation in this formalism. An important point to note here is that the properties of the measures such as strong monotonicity under relevant free operations, faithfulness, as well as quantitative bounds and relations, all follow straightforwardly from our discussion in sections 3 and 4. Since these properties are often not easy to show explicitly for a given measure, one can benefit from exploiting the fact that these quantifiers are in fact atomic gauges.

We begin with the discussion of quantum coherence, as the introduced measures will form a basis for our investigation of bipartite entanglement.

5.1. k-coherence

The resource-theoretic framework of quantum coherence in finite-dimensional systems was established relatively recently [3, 6, 7, 90] (see [8] for a comprehensive overview). An extension of this concept to a hierarchy of k levels of coherence has been considered in [10, 86, 91–93] and was formalised as the resource theory of k-coherence in [94]. We remark that many of the methods introduced in this section can be used with non-orthogonal bases, thus applying also to resource theories of superposition which generalise quantum coherence [10, 86, 91, 95].

Let us begin with the definition of the most general notion of quantum coherence. Since quantum coherence is based on superposition, it is fundamentally a basis-dependent concept. The set of free pure states in this resource theory, which we will denote as I, corresponds to state vectors which have only one coefficient in a fixed orthonormal basis \{\ket{i}\}, that is, each free pure state vector is a normalised scalar multiple of a basis vector. The free density matrices, defined in the usual way as the convex hull of \{\ket{\psi}\bra{\psi} | \ket{\psi} \in I\}, are called the incoherent states. Any state which cannot be written as a convex combination of incoherent pure states is then coherent, and can be used as a resource.

In some applications, however, not every coherent state is useful for the considered physical tasks [10, 86, 91–94]—in these circumstances, a fine-grained quantification of quantum coherence is necessary. Given a fixed orthonormal basis \{\ket{i}\}, the coherence rank \text{CR}(\ket{\psi}) is defined as the cardinality of the state vector \ket{\psi}, that is, the number of non-zero coefficients in this basis. The set of free pure states is then given by \[ I^k = \{ \ket{\psi} | \text{CR}(\ket{\psi}) \leq k, \braket{\psi}{\psi} = 1 \} \]
and we extend this to mixed states as done previously; for the simplicity of notation, we will hereafter work with the convex hull directly:

\[
C^k_+ = \text{conv} \{ |\psi\rangle\langle\psi| | \ket{\psi} \in I^k \}.
\]  
(105)

Any state \rho \in C^k_+ is then a free state in the resource theory of k + 1-coherence, with all states \rho \notin C^k_+ being k + 1-coherent. Note that \(k = 1\), that is the quantification of 2-coherence, corresponds to the standard notion of quantum coherence, where the only resource-free states are convex combinations of the basis projectors; also, note that \(C^d_+ = \mathbb{D}\). Let us also define the corresponding set \(C^k = \text{conv} \{ |\psi\rangle\langle\phi| | \ket{\psi} \in I^k, \ket{\phi} \in I^k \} \) as before.

5.1.1. \(k = 1\) and \(k = d\). The resource theory of quantum coherence (\(k = 1\)) has been investigated in many works, and a variety of quantifiers have been considered [7, 23, 34, 35, 68, 96, 97]. Applying the formalism of this work to the states \(C^k_+\) with \(k = 1\), one can notice that we have:
\[
\Gamma_{\mathcal{I}}(|\psi\rangle) = \inf \left\{ \sum_i c_i \mid \psi = \sum_i c_i |v_i\rangle, c_i \in \mathbb{R}_+, |v_i\rangle \in \mathcal{I} \right\} = \inf \left\{ \sum_i |c_i| \mid \psi = \sum_i c_i |\tilde{v}_i\rangle, c_i \in \mathbb{C} \right\} = \|\psi\|_{\ell_1},
\]

(106)

Following in a similar way for the other quantifiers, we obtain several known norms and gauges for Hermitian matrices, many of which have been used as coherence measures:

<table>
<thead>
<tr>
<th>Gauge</th>
<th>Also known as</th>
<th>Gauge</th>
<th>Also known as</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Gamma_{\mathcal{I}})</td>
<td>Vector (\ell_1) norm (|\cdot|_{\ell_1})</td>
<td>(\Gamma_{\mathcal{L}})</td>
<td>Vector (\ell_2) norm (|\cdot|_{\ell_2})</td>
</tr>
<tr>
<td>(\Gamma_{\ell_1})</td>
<td>Vector infinity norm (|\cdot|<em>{\ell</em>\infty})</td>
<td>(\Gamma_{\ell_2})</td>
<td>Vector (\ell_2) norm (|\cdot|_{\ell_2})</td>
</tr>
<tr>
<td>(\Gamma_{C})</td>
<td>Element-wise (\ell_1) norm (|\cdot|_{\ell_1})</td>
<td>(\Gamma_{C})</td>
<td>Trace (nuclear) norm (|\cdot|_1)</td>
</tr>
<tr>
<td>(\Gamma_{C})</td>
<td>Element-wise max norm (|\cdot|<em>{\ell</em>\infty})</td>
<td>(\Gamma_{C})</td>
<td>Operator norm (|\cdot|_\infty)</td>
</tr>
<tr>
<td>(\Gamma_{C})</td>
<td>Maximum of diagonal elements and 0</td>
<td>(\Gamma_{C}^+)</td>
<td>Max. of eigenvalues and 0</td>
</tr>
<tr>
<td>(\Gamma_{C}^{\cup(-C)})</td>
<td>Maximum of absolute diagonal elements</td>
<td>(\Gamma_{C}^{\cup(-C)})</td>
<td>Numerical radius ([48])</td>
</tr>
<tr>
<td>(R_{C+}^{\ell_1})</td>
<td>Standard robustness of coherence</td>
<td>(R_{C+}^{\ell_1})</td>
<td>Trace of positive part (-1)</td>
</tr>
<tr>
<td>(R_{C+}^{\ell_2})</td>
<td>Generalised robustness of coherence ([23])</td>
<td>(R_{C+}^{\ell_2})</td>
<td>Trace of positive part (-1)</td>
</tr>
<tr>
<td>(\Gamma_{C+}^{\ell_1}-1)</td>
<td>Coherence concurrence ([34, 35])</td>
<td>(\Gamma_{C+}^{\ell_2}-1)</td>
<td>Trace norm (-1)</td>
</tr>
<tr>
<td>(1-\Gamma_{C+}^{\ell_1})</td>
<td>Geometric measure of coherence ([96])</td>
<td>(1-\Gamma_{C+}^{\ell_2})</td>
<td>—</td>
</tr>
</tbody>
</table>

where by ‘\(\ldots\)' we denote functions which, to our knowledge, have not been previously defined in the literature explicitly or do not correspond to easily characterisable quantities, although they can of course be defined in a similar manner. By the trace of the positive part of a Hermitian matrix \(M\) we understand the quantity \(\text{Tr}(\Pi_+ M \Pi_+)\) with \(\Pi_+\) denoting the orthogonal projection onto the subspace spanned by the non-negative eigenvalues of \(M\). Further, we recall that \(\Gamma_{C,\cup(-C^\perp)}\) corresponds to the trace norm itself for all Hermitian matrices \([54]\).

Note also that the set \(C_+^1\) only spans the set of diagonal matrices in the given basis, which means that the measure \(R_{C_+}^{d^1}\) is not a valid measure of 2-coherence as it is infinite for \(\rho \notin C_+^1\).

5.1.2. \(1 \leq k \leq d\). We will now consider the extension of the atomic gauge formalism to arbitrary \(k\). Several of the measures in this resource theory have been defined in the literature already: they are the geometric measure of \(k\)-coherence \([86]\) and the generalised robustness \(R_{C_+}^{d^k}\) \([94]\). All of the other measures that we have considered in section 3 can be defined analogously. We will consider some explicit examples.

The sets \(C_d^k\) for \(k \geq 2\) have been shown to span the whole space \(\mathbb{H}\) \([94]\), and so \(R_{C_+}^{d^k}\) can be used as a quantifier for \(k \geq 2\). The other considered measures \(\Gamma_{\mathcal{I}}, \Gamma_{\mathcal{C}}, \Gamma_{C_+}^{\ell_1}\), and \(R_{C_+}^{d^k}\) have no domain problems because \(\text{span}(\mathcal{I}^k) = \mathbb{C}^d \forall k\).

The atomic vector norm on the set \(\mathcal{I}^k\), called the \(k\)-support norm \(\|\cdot\|_{(k)}\) was introduced in \([98]\) in the context of machine learning and optimisation. The norm is in fact exactly computable for any \(k\).
Definition 24 (Argyriou et al [98]). Let \( \mathcal{P}_k \) be the set of all possible subsets of \( \{1, \ldots, d\} \) of at most \( k \) elements, and let \( \text{esupp}(|x|) := \{ i \mid x_i \neq 0 \} \) where \( x_i \) is the \( i \)th coefficient of \( |x| \) in the given basis. The \( k \)-support norm\(^1\) is defined as the atomic norm for the set \( \mathcal{I}^k \) and is given by

\[
\Gamma_{\mathcal{I}^k}(|x|) = \|x\|_{(k)} := \inf \left\{ \sum_{i \in \mathcal{P}_k} \|\nu_i\|_{\ell_2} \mid \text{esupp}(|\nu_i\rangle) \subseteq I, \sum_{i \in \mathcal{P}_k} \|\nu_i\| = |x| \right\}
\]

\[
= \left( \sum_{i=1}^{k-r} |x_i|^2 + \frac{1}{r+1} \left( \sum_{j=k-r}^{d} |x_j|^2 \right)^2 \right)^{1/2} \tag{107}
\]

where \( x^i \) denotes the coefficients of \( |x| \) sorted in non-increasing order by magnitude (\( |x_1^i| \geq |x_2^i| \geq \ldots \)), and \( r \) is the unique integer in \( \{1, \ldots, k-1\} \) satisfying

\[
|x_{k-r}^k| = \frac{1}{r+1} \sum_{j=k-r}^{d} |x_j^i| \geq |x_{k-r-1}^k|
\]

or 0 if no such integer exists.

It is explicit from equation (107) that the \( k \)-support norm interpolates between the \( \ell_1 \) and \( \ell_2 \) norms for vectors—indeed, we have that \( \|\| \|_{(1)} = \|\|_{\ell_1} \) and \( \|\| \|_{(2)} = \|\|_{\ell_2} \).

The polar (dual norm) of the \( k \)-support norm is given by

\[
\|x\|^0_{(k)} = \sqrt{\sum_{i=1}^{k} |x_i|^2},
\]

that is, the \( \ell_2 \) norm of the \( k \) largest coefficients. In general, we have that \( \|\| \|_{\ell_1} \geq \|\| \|_{(k)} \geq \|\| \|_{\ell_2} \geq \|\| \|_{(d)} \geq \|\| \|_{\ell_\infty} \).

We remark that an alternative way to derive the exact formula for the \( k \)-support norm is to start with the dual norm \( \|\| \|_{(k)} \), which is easier to compute explicitly [86], and apply the duality result from [101] as has been done in [102] for entanglement.

The atomic norm \( \Gamma_{\mathcal{C}_k} \) on the set \( \mathcal{C}^k \) is the \( (k,k) \)-trace norm defined as [45, 46]:

\[
\|\rho\|_{(k,k)} = \inf \left\{ \sum_i \|a_i\| \|b_i\| \|_{(k)} \mid \rho = \sum_i |a_i\rangle\langle b_i| \right\}
\]

\[
= \inf \left\{ \sum_{i,j \in \mathcal{P}_k} \|Z_{i,j}\|_1 \mid \text{esupp} (Z_{i,j}) \subseteq I \times J, \rho = \sum_{i,j} Z_{i,j} \right\} \tag{110}
\]

\[
\|\rho\|^0_{(k,k)} = \sup \left\{ \|\langle a|\rho|b\rangle\| \mid |a\rangle, |b\rangle \in \mathcal{V}^k \right\} \tag{111}
\]

where \( \text{esupp}(M) \) is defined for a matrix with elements \( M_{ij} \) as \( \text{esupp}(M) = \{ (i,j) \mid M_{ij} \neq 0 \} \). This norm interpolates between the entrywise \( \ell_1 \) norm for \( \|\| \|_{(1,1)} \) and the standard trace norm.

---

\(^1\)The terminology of ‘\( k \)-support’ comes from the fact that the set of non-zero coefficients of a matrix is frequently referred to as ‘support’ in statistical learning and optimisation literature [99]. Since this differs from the usual definition of ‘support’ in quantum information, where it is used to mean the orthogonal complement of the kernel of an operator [100], to avoid confusion we use the notation of \( \text{esupp} \) to refer to the ‘element-wise support’.
for $\|\cdot\|_{(dA,B)}$. The $(k,k)$-trace norm is therefore a natural generalisation of the $\ell_1$-norm of coherence, a fundamental measure of quantum coherence [7, 75], to the formalism of $k$-coherence.

While $\|\cdot\|_{(k,k)}$ is in general NP-hard to compute exactly, a numerical algorithm to approximate it was introduced in [45]. Note also that the generalised robustness of $k$-coherence $R_{C_k}^{(d)}$ was shown to be computable with a semidefinite program (SDP) [94]. It follows easily that the same property holds for the standard robustness $R_{C_k}$, and since this quantity is well-defined for any $k \geq 2$, we obtain tight bounds for the $(k,k)$-trace norm as

$$R_{C_k}^{(d)}(\rho) \geq \|\rho\|_{(k,k)} - 1 \geq R_{C_k}(\rho). \quad (111)$$

The convex roof extension of the $k$-support norm $\Gamma_{C_k}^{(d)}$ is the natural convex roof measure in this formalism. By theorem 19, both the convex roof–extended $k$-support norm as well as the $(k,k)$-trace norm are strongly monotonic under $k$-incoherent operations [94]. We remark that another convex roof-based measure was defined in [92], based on an entanglement monotone called $k$-concurrence; it is not a generalisation of the $\ell_1$ norm in the present framework, and we will compare the measures quantitatively in the next section.

5.2. Bipartite entanglement

Let $|\psi\rangle \in \mathbb{C}^{d_A} \otimes \mathbb{C}^{d_B}$ denote a bipartite pure state shared between two parties $A$ and $B$, with the dimensions of the corresponding spaces denoted as $d_A$ and $d_B$. A pure state is called separable or a product state (in the $A|B$ bipartition) if it can be written as $|\psi\rangle = |\psi_A\rangle \otimes |\psi_B\rangle$, and entangled otherwise. We denote the set of all product state vectors as $V$, and we define $S_k$ to be the set of all separable density matrices defined through the convex hull. The Schmidt rank of a state $|\psi\rangle$ is defined as

$$\text{SR}(|\psi\rangle) = \min \left\{ r \in \mathbb{N} \left| \text{ } |\psi\rangle = \sum_{i=1}^{r} \lambda_i |c_i\rangle \langle v_i|, \text{ } |v_i\rangle \in V \right. \right\}. \quad (113)$$

Then $|\psi\rangle$ is unentangled if and only if $\text{SR}(|\psi\rangle) = 1$, and in general we have $1 \leq \text{SR}(|\psi\rangle) \leq \min(d_A,d_B)$. A crucial property of bipartite entanglement is that every state can be expressed in the so-called Schmidt decomposition as

$$|\psi\rangle = \sum_{i=1}^{\text{SR}(|\psi\rangle)} \lambda_i |a_i\rangle \otimes |b_i\rangle \quad (114)$$

where $\{|a_i\rangle\}$ and $\{|b_i\rangle\}$ form orthonormal bases for $\mathbb{C}^{d_A}$ and $\mathbb{C}^{d_B}$, respectively, and the terms $\lambda_i$ are called Schmidt coefficients.

As previously, we now want to consider situations where not all entangled states are resourceful; that is, for our particular task, a state with at least a given Schmidt rank $k$ is necessary, and we would like to quantify the entanglement corresponding to a particular Schmidt rank [50, 52, 103, 104]. We define the Schmidt vector $\lambda(|\psi\rangle)$ of a state $|\psi\rangle$ to be the vector consisting of its Schmidt coefficients including the zero terms, so that it is always $\min(d_A,d_B)$-dimensional. Since the Schmidt rank of a state corresponds to the cardinality of the Schmidt vector just as the coherence rank corresponds to the cardinality of the state vector in the given basis, in the case of pure states, the resource theory of bipartite entanglement of Schmidt rank $k+1$ can be seen to correspond to the resource theory of $k+1$-coherence applied to the Schmidt vector. Indeed, this relation between the two resource theories has been used to relate the corresponding quantifiers [105–107].
We now define the relevant sets of free pure state vectors and free density matrices as, respectively:

\[ V_k = \{|\psi\rangle \mid \text{SR}(|\psi\rangle) \leq k, \langle \psi | \psi \rangle = 1 \} \]

\[ S^+_k = \text{conv}\{ |\psi\rangle \langle \psi | \mid |\psi\rangle \in V_k \} \]

(115)

and define the corresponding set

\[ S_k = \text{conv}\{ |\psi\rangle \langle \phi | \mid |\psi\rangle, |\phi\rangle \in V_k \} \]

(116)

\( S^+_1 \) is then the set of separable states, and \( S^+_k = \mathbb{D} \). A mixed state \( \rho \in S^+_k \) is said to have Schmidt number (at most) \( k \) [52]. The dual cone \( S^+_k \) defines the set of the so-called \( k \)-block positive operators [108].

Note that for any \( k \), we have that \( \text{span}(V_k) = \mathbb{C}^d \) and \( \text{span}(S^+_k) = \mathbb{H} \) [109], which in particular means that all of the considered functions are finite for any density matrix, and that the relevant symmetric gauges \( \Gamma_{V^*_k}, \Gamma_{S^*_k} \cup (-S^*_k), \Gamma_{S^*_k} \) all define valid norms.

The set of operations of interest in the theory of entanglement—LOCC—is a strict subset of both the resource non-generating (separability-preserving) and the resource-free (separable) operations [67], which by the results of section 4 means that all of the considered measures are strong monotones under LOCC. We stress that the measures introduced herein are monotonic not only under free operations which do not generate entanglement, but also under a larger set of operations which do not generate entanglement of Schmidt rank \( k+1 \).

5.2.1. \( k = 1 \). For \( k = 1 \), we obtain many familiar measures and quantifiers in this formalism:

<table>
<thead>
<tr>
<th>Gauge</th>
<th>Also known as</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Gamma_{V^*_1} )</td>
<td>Sum of Schmidt coefficients</td>
</tr>
<tr>
<td>( \Gamma_{V^*_1}^\text{max} )</td>
<td>Largest Schmidt coefficient</td>
</tr>
<tr>
<td>( \Gamma_{S^1} )</td>
<td>Greatest cross norm (projective tensor norm) [32, 58]</td>
</tr>
<tr>
<td>( \Gamma_{S^1}^\text{op} )</td>
<td>Schmidt operator norm (injective tensor norm) [50]</td>
</tr>
<tr>
<td>( \Gamma_{S^1}^\text{pr} )</td>
<td>—</td>
</tr>
<tr>
<td>( \Gamma_{S^1}^\text{pr} \cup (-S^1) )</td>
<td>Product numerical radius [110]</td>
</tr>
<tr>
<td>( R_{S^1}^\text{pr} )</td>
<td>Robustness of entanglement [29]</td>
</tr>
<tr>
<td>( R_{S^1}^\text{gr} )</td>
<td>Generalised robustness of entanglement [29, 30]</td>
</tr>
<tr>
<td>( \Gamma_{S^1}^\text{pr} - 1 )</td>
<td>((2\times)) convex roof–extended negativity [33]</td>
</tr>
<tr>
<td>( 1 - \Gamma_{S^1}^\text{op} )</td>
<td>Geometric measure of entanglement [84]</td>
</tr>
</tbody>
</table>

The vector gauge \( \Gamma_{V^*_1} \) is the \( \ell_1 \) norm of the Schmidt vector, corresponding to the sum of Schmidt coefficients and constituting a convex relaxation of the Schmidt rank of a pure state.

The negativity of a state is defined as \( N(\rho) = \frac{1}{2} \left( \| \rho^{\text{Ts}} \| _1 - 1 \right) \) [28, 109], where \( \rho^{\text{Ts}} \) denotes the partial transpose. The negativity of pure states is precisely [28]

\[ N(|\psi\rangle \langle \psi|) = \sum_{j < k} \lambda_j \lambda_k = \frac{\Gamma_{V^*_1}(|\psi\rangle)^2 - 1}{2} , \]

(117)

which means that the convex roof–based quantifier \( \Gamma_{S^1}^\text{pr} \) is (twice) the convex roof–extended negativity. This function was proposed as an alternative generalisation of concurrence to systems beyond two qubits [33], and it was further suggested as the measure most suitable to characterise the so-called monogamy relations of entanglement between qudits [111–116],
which the concurrence fails to satisfy. Here we also see that the convex roof–extended negativity arises as the natural gauge-based generalisation of the concurrence. The faithfulness and strong monotonicity of \( \Gamma_{S^k}^{\varphi} \) under separable operations follow from theorem 19.

It has been pointed out that the quantity \( 2N(\rho) + 1 \) can be used to lower bound the Schmidt number of a given quantum state [117]. The atomic gauge function formalism provides a geometric intuition and justification for this statement, in the sense that for pure states \( \Gamma_{\varphi}(|\psi\rangle) = 2N(|\psi\rangle\langle\psi|) + 1 \) is exactly a natural convex relaxation of the Schmidt rank, and the functions \( \Gamma_{S^k}^{\varphi}(\rho) \), \( \Gamma_{S^k}^{\varphi}(\rho) \) as well as the robustness measures all constitute convex lower bounds to the Schmidt number of a state by our discussion in section 3.1.1. The negativity itself then constitutes a lower bound to the gauges (see section 5.2.3 below).

The atomic norm \( \Gamma_{S^k}^{\varphi} \) is the greatest cross norm, a quantifier introduced by Rudolph [31, 32]. It can alternatively be written as

\[
\Gamma_{S^k}^{\varphi}(\rho) = \inf \left\{ \sum_i \| X_A^{(i)} \|_1 \| X_B^{(i)} \|_1 \left| \rho = \sum_i X_A^{(i)} \otimes X_B^{(i)}, \lambda X_A^{(i)} \in \mathbb{C}^{d_A \times d_A}, \lambda X_B^{(i)} \in \mathbb{C}^{d_B \times d_B} \right. \right\}. 
\]

(118)

5.2.2. \( k \geq 1 \) The generalisation of many of the above quantities to the set of bipartite states with a given Schmidt number \( k \) was considered by Johnston and Kribs in [50, 102, 118], and the generalised robustness in [119]. Similarly to the case of coherence, we obtain a hierarchy of quantifiers, each corresponding to a different level of bipartite entanglement.

The quantity \( \Gamma_{\varphi}^{\varphi} \) is nothing but the \( k \)-support norm of the Schmidt vector, \( \| \lambda(\cdot) \|_{(k)} \). This gives a natural generalisation of the convex roof–extended negativity to a measure of Schmidt rank \( k \) entanglement:

\[
\Gamma_{S^k}^{\varphi}(\rho) = \inf \left\{ \sum_i p_i \| \lambda(|\psi_i\rangle) \|_{(k)} \left| \rho = \sum_i p_i |\psi_i\rangle \langle \psi_i|, p_i \in \mathbb{R}_+, \sum_i p_i = 1 \right. \right\}. 
\]

(119)

Another common convex roof–based measure of Schmidt rank \( k \) entanglement is Gour’s \( k + 1 \)-concurrence [120]—a comparison between the values of \( \Gamma_{\varphi}^{\varphi} \) and the \( k + 1 \)-concurrence on pure states can be found in figure 1.

The norm \( \Gamma_{S^k}^{\varphi} \) generalises the greatest cross norm to a faithful quantifier of entanglement of a given Schmidt rank [102]. One can also express \( \Gamma_{S^k}^{\varphi} \) as the nuclear norm

\[
\Gamma_{S^k}^{\varphi}(\rho) = \inf \left\{ \sum_i \| \lambda(|x_i\rangle) \|_{(k)} \| \lambda(|y_i\rangle) \|_{(k)} \left| \rho = \sum_i |x_i\rangle \langle y_i| \right. \right\}. 
\]

(120)

We remark that, just as in the case of coherence, the robustnesses \( R_{S^k}^{S^k} \) and \( R_{S^k}^{D} \) provide tight upper and lower bounds for this norm. Further, we establish that \( R_{S^k}^{D} \) reduces on pure states to the \( k \)-support norm of entanglement, thus generalising the known relation between the robustness of entanglement and negativity [29].

Note that the polar gauge \( \Gamma_{S^k}^{\varphi} \) can be computed exactly in small dimensions, and in general bounded by semidefinite programs [118], allowing for an efficient characterisation of \( k \)-block positive operators [50].

5.2.3. Remarks about the resource theory of negative partial transpose. Letting \( T_B \) denote the transpose map on \( \mathbb{C}^{d_a} \), the partial transpose of \( \rho \) is given by \( \rho^{T_B} = (\mathbb{1}_A \otimes T_B)(\rho) \). The set of states with positive partial transpose (PPT) is then \( \text{PPT}_+ = \{ \rho \in \mathbb{D} \mid \rho^{T_B} \in \mathbb{P}_+ \} \).
It is well-known that $S^1_1 \subseteq \text{PPT}^+$ with equality iff $d_A d_B \leq 6$ [121, 122], and that the separable operations (resource-free operations in the resource theory of bipartite entanglement) are a subset of the so-called PPT-preserving operations (resource non-generating operations in the resource theory corresponding to PPT states) [67, 122]. What this means in particular is that, by considering the resource theory in which $\text{PPT}^+$ is the set of free states, any monotone under PPT-preserving operations is an entanglement monotone under separable operations— including the quantities $R_{\text{PPT}}^\text{PPT}^+$ and $R_{\text{PPT}}^\text{PPT}^+$.

A different choice of the reference set of free states is often made, taking instead the set of unit trace Hermitian matrices with a positive partial transpose, $\text{PPT} = \{ X \in \mathbb{H} \mid (1, X) = 1, X^{T_h} \in \mathbb{H}^+_+ \}$. The gauge function formalism straightforwardly applies to such cases as well— indeed, the negativity of any mixed state, defined as $N(\rho) = \frac{1}{2} (\| \rho^{T_h} \|_1 - 1)$, can be written simply as $N(\rho) = R_{\text{PPT}}^\text{PPT}^+ (\rho)$ [22, 28]. The function $R_{\text{PPT}}^\text{PPT}^+$ was in fact mentioned in the original work of Vidal and Werner [28] as an alternative to negativity, leading to the relation $R^S_{S^1_1} (\rho) \geq R_{\text{PPT}}^\text{PPT}^+ (\rho) \geq N(\rho)$ by the set inclusion of their unit balls. More recently, other gauge functions in the resource theory of negative partial transpose have been employed to provide bounds on distillable entanglement [123] and characterise asymptotic entanglement manipulation [124].

These considerations generalise also to multipartite entanglement in the form of quantifiers such as the genuine multipartite negativity [125, 126], as we will consider explicitly in the next section.

5.3. $k$-partite entanglement

Let us now consider a system consisting of $n \geq 2$ parties, $|\psi\rangle \in \mathbb{C}^{d_1} \otimes \cdots \otimes \mathbb{C}^{d_n}$. Similarly to the hierarchy of the Schmidt rank in the case of bipartite entanglement, one can define a hierarchy of multipartite entanglement. We will take $\mathcal{P}^k$ with $1 \leq k \leq n$ to be the set of pure states which are $k$-producible—that is, they can be expressed as [127]

$$
|\psi\rangle = |\phi_1\rangle \otimes |\phi_2\rangle \otimes \cdots \otimes |\phi_m\rangle
$$

(121)

where each of the $m$ states $|\phi_i\rangle$ consists of at most $k$ parties. Since such states are at most $k$-partite entangled, they are precisely the free states in the resource theory of $k + 1$-partite entanglement.

![Figure 1. Comparison of the different Schmidt rank $k$ entanglement measures for 10^6 randomly generated pure states (uniformly distributed with respect to the Haar measure). On the x axis is the quantity $\Gamma_{\text{V}}^k (|\psi\rangle) = \| \lambda (|\psi\rangle) \|_2^2 - 1$ (with a normalisation factor $\frac{1}{d_A}$), and on the y axis is the $k + 1$-concurrence monotone from [120]. (a) $d_A = d_B = 3, k = 2$. (b) $d_A = d_B = 4, k = 2$. (c) $d_A = d_B = 6, k = 3$.](image-url)
The convex hull of the corresponding set of matrices $\mathcal{M}_+^k = \text{conv} \{ |a\rangle \langle a| \mid |a\rangle \in \mathcal{P}^k \}$ then defines the set of $k$-producible mixed states, and we analogously define $\mathcal{M}^k = \text{conv} \{ |a\rangle \langle b| \mid |a\rangle, |b\rangle \in \mathcal{P}^k \}$. Note that $\mathcal{M}_+^k$ is the set of fully separable states and $\mathcal{M}^k = \mathbb{D}$.

Unlike the theory of bipartite entanglement, our understanding of the theory of multipartite entanglement is still very limited [1, 128]. While one can straightforwardly generalise the quantities defined previously for bipartite entanglement—for instance, as the robustness of $k$-party entanglement [129], geometric measure of $k$-party entanglement [130], and product numerical radius [131]—their quantification and characterisation is in general a much more difficult task.

In the case of $k = 1$, the corresponding norm $\Gamma_{\mathcal{M}_+}$ generalises the greatest cross norm [32]. This quantity along with its dual norm $\Gamma_{\mathcal{M}_+}^\circ$ have been investigated in detail in [132], including the infinite-dimensional case. The norms $\Gamma_{\mathcal{P}_+}$ and $\Gamma_{\mathcal{M}_+}$ were in fact shown to correspond to the same concept—projective tensor norm—but defined on different spaces, the Hilbert space $\mathcal{H} \cong \mathbb{C}^{d_1} \otimes \cdots \otimes \mathbb{C}^{d_k}$ in the case of $\Gamma_{\mathcal{P}_+}$, and the Hilbert space of trace-class bounded linear operators $\mathcal{H}$ in the case of $\Gamma_{\mathcal{M}_+}$. Explicitly, one can write

$$\Gamma_{\mathcal{P}_+}(|\psi\rangle) = \inf \left\{ \sum_i \| a^{(i)}_1 \|_{\ell_1} \| a^{(i)}_2 \|_{\ell_2} \cdots \| a^{(i)}_n \|_{\ell_n} \mid |\psi\rangle \right\}$$

$$= \sum_i |a^{(i)}_1 \rangle \otimes |a^{(i)}_2 \rangle \cdots \otimes |a^{(i)}_n \rangle, \quad |a^{(i)}_j \rangle \in \mathbb{C}^{d_j} \right\}$$

(122)

$$\Gamma_{\mathcal{M}_+}(\rho) = \inf \left\{ \sum_i \| X^{(i)}_1 \|_1 \| X^{(i)}_2 \|_1 \cdots \| X^{(i)}_n \|_1 \mid \rho = \sum_i X^{(i)}_1 \otimes X^{(i)}_2 \otimes \cdots \otimes X^{(i)}_n, \right\}$$

$$X^{(i)}_j \in \mathbb{C}^{d_j \times d_j} \right\}$$

(123)

following [32, 132], where $d_j$ denotes the dimension of the Hilbert space of the $j$th system. Note that the base norm $\Gamma_{\mathcal{M}_+ \cup \mathcal{M}_+^\circ}$ can be expressed by replacing $X^{(i)}_j \in \mathbb{C}^{d_j \times d_j}$ with $X^{(i)}_j \in \mathbb{C}^{d_j \times d_j}$ in equation (123) [58].

Generalising this norm to the fine-grained classification of $k$-party entanglement, one obtains a hierarchy of norms akin to the one defined for Schmidt rank $k$ entanglement. Explicitly, we have:

$$\Gamma_{\mathcal{M}_+}(\rho) = \inf \left\{ \sum_i c_i \mid \rho = \sum_i c_i |v_i\rangle \langle w_i|, \quad |v_i\rangle, |w_i\rangle \in \mathcal{P}^k \right\}$$

$$= \inf \left\{ \sum_i \Gamma_{\mathcal{P}_+}(|v_i\rangle) \Gamma_{\mathcal{P}_+}(|v_i\rangle) \mid \rho = \sum_i |v_i\rangle \langle v_i| \right\}$$

$$\Gamma_{\mathcal{M}_+}^\circ(\rho) = \sup \left\{ \| |a\rangle \langle b| \| \mid |a\rangle, |b\rangle \in \mathcal{P}^k \right\}$$

(124)

and analogously for the other definitions. The computation of these quantities is of course not easy, especially without being able to rely on tools such as the bipartite Schmidt decomposition, although let us remark that generalisations of the Schmidt decomposition have been
proposed [133–135] and one of them in particular has been related to the quantification of the \( \Gamma_m \) norm for some special cases of states [135].

A case of particular interest is the so-called genuine \( n \)-partite entanglement, corresponding to states which are not separable across any bipartition; in other words, the resource theory whose free states are constituted by the \( (n-1) \)-producible states \( \mathcal{M}_+^{n-1} \). This case is particularly simple to consider for pure states, where it suffices to minimise the bipartite atomic gauge over all possible \( 2^{n-1} - 1 \) bipartitions of the system:

\[
\Gamma_{\mathcal{P}_{n-1}}(\vert\psi\rangle) = \min_{\text{bipartition}} \Gamma_{\mathcal{V}_{1}}^{(A|B)}(\vert\psi\rangle) \tag{125}
\]

with \( \Gamma_{\mathcal{V}_{1}}^{(A|B)} \) denoting the atomic gauge \( \Gamma_{\mathcal{V}_{1}} \) introduced in section 5.2 computed in the given bipartition \( (A|B) \). Since we have shown \( \Gamma_{\mathcal{V}_{1}}^{2} - 1 \) to be equal to twice the bipartite negativity, it means that \( \Gamma_{\mathcal{P}_{n-1}}^{2} - 1 \) is in fact equal to twice the so-called renormalised genuine multiparticle negativity (rgmn) [126]. The convex roof extension of \( \Gamma_{\mathcal{P}_{n-1}}^{2} - 1 \) then generalises the convex roof–extended negativity to a measure of genuine multipartite entanglement.

The rgmn itself, computable with a semidefinite program [126], can be used to provide lower bounds for the measures. Furthermore, we have that the quantifiers such as the generalised robustness of genuine multipartite entanglement are equal to twice the rgmn on pure states, generalising the known relation of the negativity and robustness for \( n = 2 \) [28, 30] and allowing for an efficient quantification of genuine multipartite entanglement for pure states.

The properties of the quantities introduced above such as faithfulness, strong monotonicity under free operations (which includes LOCC as a subset), quantitative bounds, and their relation to witnesses of \( k \)-partite entanglement all follow from the results of this work. We remark that since for each \( k \), \( \mathcal{P}_{k} \) and \( \mathcal{M}_{k} \) span the whole space, the considered measures all have full domain and \( \Gamma_{\mathcal{P}_{k}}, \Gamma_{\mathcal{M}_{k}}, \text{ and } \Gamma_{\mathcal{M}_{k}^{+} \cup (-\mathcal{M}_{k}^{+})} \) all define valid norms.

### 5.4. Magic states

As the final example of the application of the atomic gauge formalism, we briefly consider the resource theory of magic states, recently characterised in [13, 14, 24, 136–140]. Here, the free pure state projectors are the so-called stabiliser states, consisting of the eigenvectors of Heisenberg-Weyl operators, and states outside of their convex hull are called magic states. Since there is always a finite number of pure stabiliser states (although it scales superexponentially with the dimension of the Hilbert space [141]), the set of free density matrices is given by

\[
\mathcal{W}_{+} = \text{conv} \{ \vert v_1 \rangle \langle v_1 \vert, \ldots, \vert v_k \rangle \langle v_k \vert \} \tag{126}
\]

and forms a polytope in the space of Hermitian matrices, which means that the quantification of many measures in the atomic gauge formalism will reduce to solving a linear or semidefinite programming problem [14, 24]. We will make this explicit by expressing the optimisation problems involved in simplified forms.

To begin, let us define the non-balanced set \( \mathcal{T}' = \{ \vert v_1 \rangle, \ldots, \vert v_k \rangle \} \), where \( \{ \vert v_i \rangle \} \) are the pure stabiliser states with any complex phase. Since we require the set of free states to be balanced, the set of interest \( \mathcal{T} \subset \mathbb{C}^{d} \) is given by \( \mathcal{T}' \) symmetrised around the origin. The atomic gauge function corresponding to this set can be obtained by considering the \( d \times k \)
matrix whose columns correspond to the free states, i.e. $T = \{|v_i\}, \ldots, |v_k\rangle\rangle$, which then gives
\[
\Gamma_T(|\psi\rangle) = \min \left\{ \sum_i c_i \left| \psi = \sum_i c_i |v_i\rangle, |v_i\rangle \in T, c_i \in \mathbb{R}_+ \right. \right\}
\]
\[
= \min \left\{ \sum_i |c_i| \left| \psi = \sum_i c_i |v_i\rangle, |v_i\rangle \in T', c_i \in \mathbb{C} \right. \right\}
\]
\[
= \min_{x \in \mathbb{C}^d} \left\{ \|x\|_{\ell_1} \left| Tx = |\psi\rangle \right. \right\} \tag{127}
\]
where we do not use the Dirac notation for $x \in \mathbb{C}^d$ to differentiate the two different spaces $\mathbb{C}^d$ and $\mathbb{C}^d$. This quantity can be thought of as a convex relaxation of the stabiliser rank, quantifying the least number of stabiliser states one needs to superpose to express the state $|\psi\rangle$ [139].

Defining the set $W = \{|w_i\rangle\langle w_j| \mid |w_i\rangle, |w_j\rangle \in T\}$, it is straightforward to see from the above characterisation that the nuclear gauge of the set $W$ is given by
\[
\Gamma_W(\rho) = \min_{x \in \mathbb{C}^d} \left\{ \|X\|_{\ell_1} \mid TXT^\dagger = \rho \right. \right\}. \tag{128}
\]

By the discussion in section 4, this defines a faithful monotone of magic. Since the set $T$ spans the space $\mathbb{C}^d$, we have that $\Gamma_W$ is a valid norm for all complex matrices. Again in a similar way, we get the atomic gauges corresponding to the robustness measures as
\[
2R^{W_+}_{W_+}(\rho) + 1 = \Gamma_{W_+ \cup (-W_+)}(\rho) = \min_{x \in \mathbb{R}^d} \left\{ \|x\|_{\ell_1} \mid T\text{diag}(x)T^\dagger = \rho \right. \right\} \tag{129}
\]
\[
R^{D}_W(\rho) + 1 = \min_{x \in \mathbb{R}^d} \left\{ \|x\|_{\ell_1} \mid T\text{diag}(x)T^\dagger \succeq \rho \right. \right\}. \tag{130}
\]

Although no longer a linear program, the generalised robustness has the advantage that, once again, its quantification reduces to computing the gauge $\Gamma_T$ for pure states by theorem 10. An alternative characterisation of the above quantities in terms of generalised Bloch vectors can be obtained by following [24], where we remark that in [24] the quantity $\Gamma_{W_+ \cup (-W_+)}$ itself was referred to as the robustness of magic.

Note that the resource theory of magic states is an example of a resource theory where the standard robustness $R^{W_+}_W$ is in general strictly larger than the other measures on pure states: as an explicit example, consider the one-qubit pure state $|T\rangle\langle T| = \frac{1}{2} \left( \mathbb{1} + \frac{\sigma_x + \sigma_y + \sigma_z}{\sqrt{3}} \right)$ [142] with $\sigma_i$ being the Pauli operators. The standard robustness of this state can be computed exactly as $R^{W_+}_W(|T\rangle\langle T|) = \frac{1}{2} (\sqrt{3} - 1)$ [24], while a similar calculation for the other measures yields
\[
\Gamma_T(|T\rangle\langle T|)^2 - 1 = 2 - \sqrt{3} \approx 0.268 < R^{W_+}_W(|T\rangle\langle T|) = \sqrt{3} - 1 \approx 0.366 \tag{131}
\]
where we recall that $R^{0}_{W_+}(|T\rangle\langle T|) = \Gamma_W(|T\rangle\langle T|) - 1 = \Gamma_T(|T\rangle)^2 - 1$. However, the difference appears to become less pronounced with increasing dimension, with the two-qubit state $|T \otimes T\rangle$ having standard robustness of approx. 0.616 and generalised robustness of approx. 0.607. A comparison of the measures for a class of mixed states is plotted in figure 2.

The convex roof–based quantifier in this formalism can be defined analogously. By noting again that each $|\psi_i\rangle \in \mathcal{T}^{**}$ can be written as $|\psi_i\rangle = Ty$ for some $y \in \mathbb{C}^d$, we get that any $P \in \{|\psi_i\rangle\langle \psi_i| \mid |\psi_i\rangle \in \mathcal{T}^{**}\}$ can be expressed as $P = \sum_{i=1}^{n} |\psi_i\rangle\langle \psi_i| = TYY^\dagger T^\dagger$ for some
$Y \in \mathbb{C}^{k \times r}$, where we can take $r \leq \text{rank}(P)^2$ by Carathéodory’s theorem [47]. We can then write
\[
\Gamma_{W,\mathcal{C}}^{(i)}(\rho) = \min_{Y \in \mathcal{C}^{k \times r}} \left\{ \|Y\|_2^2 \left| TYY^\dagger T^\dagger = \rho \right. \right\}
\] (132)
where $\|Y\|_2^2 = \sum_{j=1}^k \left( \sum_{i=1}^r |Y_{ij}|^2 \right)^2$. As for other quantum resources, this problem is in general more difficult to solve than the other quantifiers.

We remark that a very similar formalism applies to any resource theory where the set of free states is finite. For example, the resource theory of quantum coherence ($k=1$) can be obtained by taking $T$ to consist of the vectors of the reference orthonormal basis, although care has to be taken about the effective domains of the measures as discussed before.

6. Conclusions

We have introduced a framework for the quantification of arbitrary convex quantum resources based on the atomic gauge functions of the corresponding sets of free states. We have shown that the formalism encompasses many commonly used measures and allows for a straightforward comparison and characterisation of the quantifiers. In addition to the measures explicitly introduced herein—such as ones based on matrix norms, the convex roof, or the robustness measures—we have shown that the framework can be applied to describe more general kinds of quantifiers, and we provided easily verifiable conditions guaranteeing that a given measure satisfies desirable properties such as faithfulness and strong monotonicity under the free operations of the resource theory. Further, we have explicitly applied the results to the resource theories of quantum coherence, entanglement, and magic states, establishing a detailed characterisation of many known monotones as well as introducing novel measures for the resources.

The results presented here can be generalised in several ways. Firstly, note that the formalism of gauge functions allows for an application of the same concepts to infinite-dimensional spaces, as has already been done for entanglement in [132, 143]. Secondly, while we focused on the application of our framework to quantum resource theories, it can of course be used for arbitrary convex sets, beyond quantum resources and quantum states. It would also be interesting to investigate in more detail the relation between quantifiers based on atomic gauges and ones based on distance measures [66, 81], as well as quantifiers which are defined through algebraic properties but can nevertheless admit a geometric interpretation—such as measures of entanglement obtained from polynomial invariants [144–147].
We hope that our investigation into the convex geometry of measures of quantum resources will contribute to a better understanding of the properties and interrelations between various resource quantifiers, as well as provide an accessible framework to define and characterise the measures of any given convex quantum resource, complementing the recent efforts to establish a unified mathematical description of convex resources [16, 17, 20, 148].

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