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SPECIAL TOPIC — Quantum computing and quantum sensing

A family of quantum von Neumann architecture

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We develop universal quantum computing models that form a family of quantum von Neumann architectures, with modular units of memory, control, CPU, and internet, besides input and output. This family contains three generations characterized by dynamical quantum resource theory, and it also circumvents no-go theorems on quantum programming and control. Besides universality, such a family satisfies other desirable engineering requirements on system and algorithm design, such as modularity and programmability, hence serves as a unique approach to building universal quantum computers.

Keywords: von Neumann architecture, quantum resource theory, quantum computing

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1. Introduction

A modern computer is a sophisticated physical system consisting of modular units of memory, control, CPU, internet, and input and output devices. Such an information processing system is often known as von Neumann architecture, and compared with other models for computing such as the circuit model and Turing machine, it is especially suitable to realize modularity, programmability, and automation, besides universality. It also greatly benefits algorithm design, for instance, a stored algorithm can be taken as input for a high-level algorithm to design a new one out of it.

The field of quantum computing is developing rapidly, yet there are still fundamental plights, such as the realization of error-corrected qubits, the circumvention of no-go theorems, the finding of real quantum advantages, etc. To establish the quantum von Neumann architecture is central for quantum information science, with quantum CPU, relying mainly on the circuit model, and quantum communication having been successful in the past few decades.[1] Constructing quantum memory[2] and control units[3] were more challenging due to no-go theorems, and recent progresses nevertheless show that these can be resolved.[4–7] In particular, a prototype of quantum von Neumann architecture (QvN) was proposed very recently.[6,7] This serves as the framework to systematically explore various quantum advantages and design algorithms,[8] such as quantum machine learning based on quantum memory.[9–11]

Meanwhile, an attempt to systematically unify various universal quantum computing models was carried out,[12,13] and the resource-theoretic framework[13] proves to be useful to classify them. In this work, we use the resource theory to characterize QvN and establish three models of QvN forming a family, each with distinguished features that apply to different practical settings.

The primary function of a QvN, shown in Fig. 1, can be better understood if we compare it with the classical case. The two fundamental quantum principles are the channel-state duality[14] and Heisenberg's uncertainty principle. The former motivates the use of the dual state of a channel as stored quantum programs, and the use of ebits ('Bell states') for communication,[15] while the latter characterizes quantum coherence[16] which plays various roles for all components of a QvN. A throughout description of QvN would be beyond this work,[8] yet the basic picture is that, with the interplay with a quantum control unit, quantum programs can be read out from and written into a quantum memory unit, and can also be uploaded and downloaded with the usage of a quantum internet. Quantum measurements play roles for the input, output, and also during the computation. Each of the three models contains the six modular units, and the differences of the models come from how the units work.

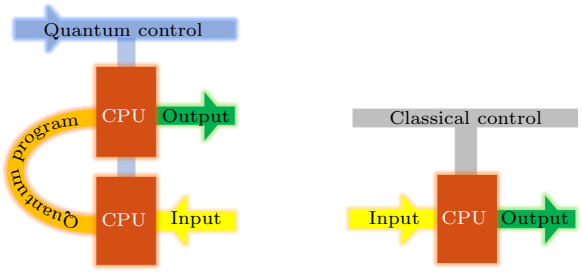


Fig. 1. Schematics of the functionality of quantum von Neumann architecture (left). They are the program, control, CPU, input and output units, with colors of yellow, blue, red, orange, and green, respectively. Besides, quantum internet is also needed to communicate quantum data. The usual circuit model is also shown for comparison (right).

A more rigorous characterization of computing models is

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based on quantum resource theory,[17] which is able to capture constraints such as those on space and time. A hierarchy of universal resources was employed to define a family of computing models, consisting of at least three generations.[13] Given the set of finite-dimensional Choi states as programs, we establish three generations of QvN, summarized in Table 1. This forms the anticipated evolution family ('e-family'),[13] and indeed, we can see a hierarchy of resources of programs from local to nonlocal ones. It shall also be noted that here we mainly rely on the resource theory of quantum programs. It is also possible to define resource theories for the task of quantum control and communication, while here their functions mostly depend on the quantum programs.

Table 1. The family of quantum von Neumann architecture (QvN) with their resource-theoretic characterization: the free set $\mathcal{F}$, free operations $\mathcal{O}$, and the set of universal resources $\mathcal{U}$. The short-hands are EBC for entanglement-breaking channels, SC for superchannels that preserve it; SEPC for bipartite separable channels, SLOCC for stochastic local operations with classical communication that preserve it; PROC stands for tensor product of local channels, S1O for stochastic one-local operations that preserve it. The relation "$a \prec b$" means the resource b is more powerful than a.

	QvN-I		QvN-II		QvN-III
$\mathcal{F}$	EBC	$\supset$	SEPC	$\supset$	PROC
$\mathcal{O}$	SC	$\supset$	SLOCC	$\supset$	S1O
$\mathcal{U}$	memory	$\prec$	bi-memory	$\prec$	nonlocal memory

This work contains the following parts. In Section 2, we present the necessary background, especially the study on quantum programmability. In Section 3, we carry out a primary resource-theoretic formulation of quantum von Neumann architectures. Indeed, we find that the resource theory can provide a proper theoretical characterization of different models. We conclude in Section 4 with some open questions.

2. Background

Quantum evolution is described by completely positive trace-preserving (CPTP) maps, also known as channels.[1] For a finite-dimensional Hilbert space $\mathcal{H}$ and the set of states $\mathcal{D}(\mathcal{H})$ on it, any quantum channel $\mathcal{E}: \mathcal{D}(\mathcal{H}) \to \mathcal{D}(\mathcal{H})$ can be represented as its dual state

$$\omega_{\mathcal{E}} := (\mathcal{E} \otimes \mathbb{1})(\omega), \tag{1}$$

usually known as a Choi state,[14] for $\omega := |\omega\rangle\langle\omega|$, and $|\omega\rangle := \sum_i |ii\rangle/\sqrt{d}$, $d = \dim(\mathcal{H})$. The state $|\omega\rangle$ is a Bell state, also known as an ebit, and it is the Choi state of an identity operator. The Choi-state formalism has been very useful, e.g., in quantum process tomography.[1]

Instead of Choi states, we often use Kraus operator-sum representation and also the quantum circuit form to represent a channel. Namely, with a set of Kraus operators $\{K_i\}$ of a channel, it is realized by a unitary evolution U such that

$$K_i = \langle i|U|0\rangle \tag{2}$$

for states $\{|i\rangle\}$ (including $|0\rangle$) forming a basis of an 'environment' or ancilla. This also forms the foundation for the so-called circuit model,[1] with initial state preparation, unitary evolution, and then followed by final measurements.

The circuit model has been well established to achieve universality, i.e., to realize any gate within a desirable accuracy by decomposing it into a sequence of well-controlled elementary gates. Examples of elementary gates are Hadamard gate $H, T = Z^{1/4}$ for Pauli Z gate, and controlled-not CNOT, and also controlled-Z gate CZ. However, there are also other requirements to build a real computer system. One such requirement is the programmability, i.e., the storage of programs as data so that they can be loaded as input to a computing device or unit. This basically leads to the von Neumann architecture.[18] For the classical case, it realizes

$$G(\boldsymbol{b} \times \boldsymbol{b}_A) = A\boldsymbol{b} \times \boldsymbol{b}'_A, \tag{3}$$

for G as the operation of a CPU, $\boldsymbol{b}$ as an input bit string, $\boldsymbol{b}_A$ as the bit-string encoding of an algorithm A. The desired output is $A\boldsymbol{b}$. The final $\boldsymbol{b}'_A$ is often ignored but can be used to recover $\boldsymbol{b}_A$.

For the quantum case, Nielsen and Chuang proved that[2] if one employs a unitary process

$$G|b\rangle|P_U\rangle = U|b\rangle|P'_U\rangle, \tag{4}$$

then $\langle P_V|P_U\rangle = 0$ for any V and U. This is often known as the 'no-programming' theorem since it states that program states $|P_U\rangle$ are actually classical, and the dimension of the program space would blow up quickly. A recent study[5] shows that this scheme can be viewed as a learning task,[19] namely, the unknown U has to be learned and then downloaded to act on input $|b\rangle$, and such learning can only be approximated with limited accuracy. If such a limited accuracy is acceptable, then this indeed can form a scheme of QvN which will be studied in Section 3.

For quantum algorithms, we often use observable instead of states to carry the final results. This motivates a different approach to constructing quantum programs.[6] Below we briefly review its construction. It employs Choi states as quantum programs and uses measurements to read and write operations. From Eq. (1), we know Choi states are bipartite, we will call the 1st (2nd) part as 'head' ('tail'). Given a program $\omega_{\mathcal{E}}$, an initial input state ρ is written into the tail by a binary measurement

$$\{\sqrt{\rho^{\mathrm{T}}}, \sqrt{\mathbb{1} - \rho^{\mathrm{T}}}\}, \tag{5}$$

and the final output in terms of an expectation value $\mathrm{tr}(\mathcal{A}\mathcal{E}(\rho))$ for observable $\mathcal{A}$ can be read out from the head.[6] Note the superscript T is the transpose. This leads to the universality to simulate any quantum algorithm in the usual circuit model whose input needs to be prepared first.[7] The no-programming

theorem is circumvented as here it does not request the final state ($U|b\rangle$), instead, it only needs values of observable without learning the algorithm U itself.

Besides the input and output by measurements, one can also do program conversion and composition. The conversion of a program $\omega_{\mathcal{E}}$ to another $\omega_{\mathcal{F}} = \hat{\mathcal{S}}(\omega_{\mathcal{E}})$ is by the so-called superchannel,[20] which in general can be realized by attaching ebits and then execute separable unitary followed by measurements;[7] namely,

$$\hat{\mathcal{S}}(\omega_{\mathcal{E}}) = \mathrm{tr}_{\mathrm{e}}\mathcal{V}\otimes\mathcal{U}(\omega_{\mathcal{E}}\otimes\omega), \tag{6}$$

with tr_{e} as the trace on the head of the ebit with projection to $|0\rangle$ on its tail, and the unitary $\mathcal{V}$ ($\mathcal{U}$) acts on the wires of heads (tails). Therefore, a superchannel $\hat{\mathcal{S}}$ can be further stored as a Choi state $\omega_{\hat{\mathcal{S}}}$, and then acted upon by another superchannel, leading to the so-called high-order operations.[21]

The composition of two programs relies on a generalization of quantum teleportation.[15] From a point of view of symmetry, the standard teleportation is $Z_d \times Z_d$ symmetric, with the qudit Pauli operators as its projective representation. The symmetry can be extended to SU(d) by grouping the nontrivial Pauli byproducts together.[6] This enables the deterministic composition of any unitary programs $\{|\omega_{U_i}\rangle\}_{i\in\mathcal{I}}$ to form $|\omega_{\prod_i U_i}\rangle$.

3. Resource-theoretic formulation

Now we study the resource-theoretic formulation of QvN in order to identify the quantum resources and classify different cases. A universal resource theory is defined by four sets

$$(\mathcal{F}, \mathcal{O}, \mathcal{R}, \mathcal{U}) \tag{7}$$

with a set of free states $\mathcal{F}$, a set of free operations $\mathcal{O}$, a set of resource states $\mathcal{R}$, and a set of universal resources $\mathcal{U} \subset \mathcal{R}$.[13] We will see below the generations in the QvN family rely on different forms of programs and operations on them. For simplicity, we assume classical control and focus on operations on programs.

3.1. QvN-I

For the 1st generation denoted as QvN-I, we require no explicit structure of the space $\mathcal{H}$, and no constraint (e.g., on locality or energy) for the channels. The primary feature of programs $\omega_{\mathcal{E}}$ is the entanglement contained in the ebit ω. Therefore, we identify the set of entanglement-breaking (EB) channels with the form

$$\mathcal{E}_{\mathrm{EB}}(\rho) = \sum_i \mathrm{tr}(F_i\rho)\sigma_i \tag{8}$$

as the free set $\mathcal{F}$, for $\{F_i\}$ as a POVM, each σ_i a state.[22] This means that the input data ρ is replaced by σ_i, with only the probability $\mathrm{tr}(F_i\rho)$ depending on ρ. The dual state of $\mathcal{E}_{\mathrm{EB}}$ is separable; therefore, it is natural to identify the set of free operations $\mathcal{O}$ as the superchannels that preserve the Choi-state form. For instance, the local operations on the tail need to be unital as the local state for the tail is completely mixed.

All channels that do not break entanglement are now resources, and the universal set $\mathcal{U}$ is the unitary programs which have the same entanglement with the ebit ω. This is analogous to the resource theory of quantum memory.[9,10] For QvN-I, the composition of programs can be treated as free, while the conversion of programs by superchannels will consume ebits. Furthermore, it is more important to identify the computational power of the free setting. We find it is at least as powerful as classical computers, namely, it can simulate any classical algorithm, hence can also describe a classical von Neumann architecture, for instance.

A random or stochastic algorithm can be described by a stochastic process

$$\boldsymbol{p} \mapsto \boldsymbol{q} = S\boldsymbol{p} \tag{9}$$

for a stochastic matrix $S = [S_{ij}]$, which can be simulated by a POVM $\{F_i\}$ with

$$S_{ij} = \langle j|F_i|j\rangle \tag{10}$$

as a special type of EB channels, for $\{|j\rangle\}$ as an orthonormal basis for the column index of S. What a classical von Neumann architecture can do with bits and pbits, e.g., copying, reading and writing can be simulated by EB channels. There can also be quantum coherence in the states out of EB channels; however, the coherence cannot propagate due to the breaking of entanglement. Whether there is an advantage over the classical case is left for further exploration.

It is intriguing to compare the resource theory of quantum programs with that for coherence or entanglement, defined for the amplitude family based on the circuit model.[13] In the setting of QvN-I, the ebit ω as a program is used to propagate quantum coherence, while coherence itself (in a non-diagonal state[16]) is created by measurement or unitary evolution. So quantum program (or memory) is different from coherence as universal resources. The ebit ω is also the universal resource of entanglement defined relative to biseparable states with a locality constraint. We will see below that, actually the dynamical analog of ebit is entangling bipartite channels, leading to the model of QvN-II.

3.2. QvN-II

For a bipartite system $\mathcal{H}_A \otimes \mathcal{H}_B$, a bipartite channel $\mathcal{E}^{AB}$ is separable if its Choi state $\omega_{\mathcal{E}^{AB}}$ is separable for the $A|B$ partition. It is straightforward to establish the resource theory with the set of separable Choi states $\omega_{\mathcal{E}^{AB}}$ as the free set

$\mathcal{F}$, and stochastic local operation with classical communication (SLOCC) that preserves it as the free operation $\mathcal{O}$, and resources as entangling bipartite channels. For instance, the CNOT gate is entangling and its entanglement is maximal for the two-qubit system.

This motivates our formulation of QvN-II. For qubits, we identify the set of all unitary gates that are locally equivalent to CNOT as $\mathcal{U}$. The building blocks are the programs ω_H, ω_T, and ω_{CNOT}, for the Hadamard gate $H, T = Z^{1/4}$ for Pauli Z gate, forming a universal gate set $\{H, T, \text{CNOT}\}$.[1] The composition of them can realize any quantum algorithm.

As shown in Fig. 2, a computation in QvN-II is a 'tailed' circuit, with input at the tail and output at the head, and composition in the middle. A composition is a teleportation acting on a tail wire and a head wire. A qubit gate, H or T, composed before a CNOT requires a standard teleportation as the Pauli byproduct can pass through the CNOT gate, while a qubit gate composed after a CNOT requires the SU(2) covariant teleportation as in this case, the Pauli byproduct only passes through when the full symmetry SU(2) is available. It is clear to see all Pauli byproducts are pulled out to the end of the circuit, hence can be corrected. The cost is proportional to the spacetime volume of a circuit, namely, the total number of elementary gates in it.

This model appears as a measurement-based quantum computing, but there are key differences. In the teleportation-based scheme,[23] gates are not pre-stored as their Choi states. The CNOT gates are stored in the cluster state,[24] but the qubit gates are from the single-qubit measurements in rotated bases. A more fundamental difference is that the information flow in QvN-II is of depth-one, see Fig. 3(a). Modular byproducts, the composition serves as an ebit which is an identity gate to propagate information. This leads to a key feature of tailed circuits that we name as "switchability" of gates (Fig. 3(b)). In details, an ebit is attached to a head of a program, forming a "triode" of heads. As shown in Fig. 3(c), one needs to apply a CNOT gate between certain wires, which is the first step in a composition. This allows the possibility to switch on or off a gate by completing one of the two information flow paths (and erasing the other by CNOTs). Such a switchability allows the correction of wrong gates during a circuit, and also yields novel programmability of circuits. Our recent work in progress shows that this setting is natural to construct programmable quantum CPU.[8]

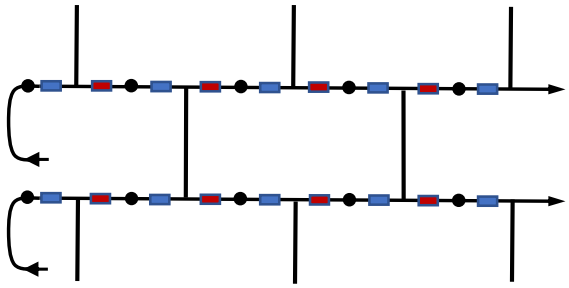


Fig. 2. Schematics of a circuit in QvN-II. The evolution of each qubit defines a local part, with the entangling gates (vertical lines) as universal resources. The connection between any two programs is a composition via standard (blue box) or SU(2) covariant (red box) teleportation. A black dot represents a qubit gate.

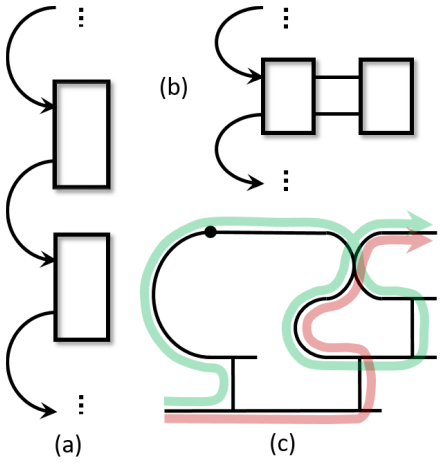


Fig. 3. (a) The information flow in QvN-II. Each box is a composition. (b) Schematics for the switchability. (c) A switchable program with an "on" path (green) and "off" path (red). Vertical lines represent CNOT gates, or CZ gates equivalently. The black dot is a qubit program, and the black crossing wires represent the swap gate. This scheme also applies to the CNOT program.

3.3. QvN-III

We now move on to construct the QvN-III model. We shall consider multipartite or nonlocal programs which in turn require more restrictive free settings. It turns out the model in Ref. [5] is the right starting point. With a generalized sine state $|\Phi\rangle$ acting on $2n$ qudits,

$$|\Phi\rangle = \bigoplus_{\lambda} \sqrt{q_\lambda} |\omega_\lambda\rangle |\omega_{m_\lambda}\rangle, \tag{11}$$

for q_λ being positive only depending on the group SU(d), the output $U|\varphi\rangle$ is approximated to the accuracy $\varepsilon \sim 1/n^2$ by the state

$$\int d\hat{U} (\hat{U} \otimes |\eta_{\hat{U}}\rangle\langle\eta_{\hat{U}}|) |\varphi\rangle |p_U\rangle \tag{12}$$

for a covariant POVM $\{\eta_{\hat{U}}\}$ formed by states $|\eta_{\hat{U}}\rangle$ and a program state

$$|p_U\rangle = (U^{\otimes n} \otimes \mathbb{1}) |\Phi\rangle. \tag{13}$$

Here $d\hat{U}$ is the Haar measure on the group SU(d). Notably, this scheme also works optimally for learning or estimation, and can also be viewed as a covariant code.[25] Namely, let $|f\rangle = U|\varphi\rangle$ and

$$|f\rangle \mapsto |\varphi\rangle |p_U\rangle \tag{14}$$

be the isometric encoding, it is then clear that this encoding is SU(d) covariant and the POVM $\{\eta_{\hat{U}}\}$ realizes the decoding. A novel feature here is that the covariance enables blind computing, which is distinct from the other two models above and motivates the following construction.

As shown in Fig. 4, we use a nonlocal program, $\omega_{\rm cov}$, to store the whole scheme, which can be viewed as a superchannel. The decoding is stored by its circuit, with the POVM $\{\eta_{\hat{U}}\}$ realized by a projective measurement according to Naimark's dilation, and the state $|\Phi\rangle$ is stored by its preparation circuit. Both the program $|\omega_U\rangle^{\otimes n}$ and data $|\varphi\rangle$ are injected by measurements. Now with each qudit being a local subsystem, it is clear that the free set $\mathcal{F}$ is formed by transversal operations, including the read/write measurements, the free operations $\mathcal{O}$ are local and no apparent classical communication is needed, and the program $\omega_{\rm cov}$ as the universal resource $\mathcal{U}$ enables an approximate or 'quasi-exact' universality[26] due to its limited accuracy. It realizes $U|\varphi\rangle$ blindly if the input, output, and program are held by separate parties. With the technique of composition, a few blind programs $\{|p_{U_i}\rangle\}$ can also be composed together.

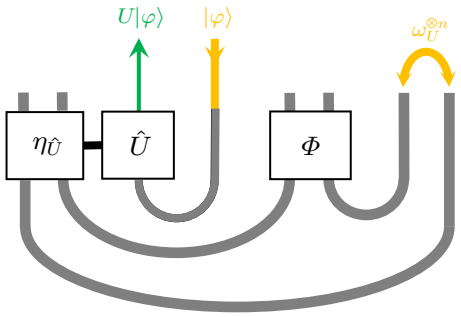


Fig. 4. Schematics for the model of QvN-III. The bold wires are multiple ebits, $\eta_{\hat{U}}$ with control to $\hat{U}$ represents the covariant POVM, Φ represents the circuit to prepare the generalized sine state. The grey part forms the program $\omega_{\rm cov}$. Note we have rotated the diagram for convenience.

We therefore established the family of QvN using the resource-theoretic framework, as summarized in Table 1. Their universal resources are the quantum memory defined by the ebits, bipartite memory defined by the CNOT gate, and the nonlocal memory from the covariant programming. We can also see a subset hierarchy of their free settings, from the largest one that can efficiently simulate any classical algorithm, to local bipartite separable channels, and to one-local channels that can only generate product states. We should note that there can be other members in this family, and the resource-theoretic characterization of a QvN can be more complete by also considering resource theories for quantum control and quantum communication.

4. Conclusion

Before we conclude, it is also beneficial to discuss briefly the implication of resource theory of quantum von Neumann architecture (QvN) from a practical point of view. There are various computational settings in practice. Often a program is generated by a software provider for users. Now our model I is suitable to describe the case when the program itself does not have a clear locality structure, say, the program is a random matrix. The user would treat it as a whole and do operations on it. The model II instead can handle multipartite programs, and a few users can use local operations and communications to accomplish more complicated tasks. In both of the two models, a user would not know the program itself, except how it generates the expected output for the chosen input. For model III, a user can know a program U itself approximately if he/she has both the input $|\varphi\rangle$ and output $U|\varphi\rangle$. A user can easily do program composition without knowing the contents of the programs. On the other hand, secure or blind computing is also possible if the input $|\varphi\rangle$, ω_U and output $U|\varphi\rangle$ are held by different users. Say, a user who needs $U|\varphi\rangle$ may not have the access to the 'key' $|\varphi\rangle$, 'lock' ω_U and 'box' $\omega_{\rm cov}$.

To summarize, we showed that QvN can be established using dynamical quantum resource theory. In the framework of QvN, it remains to see if QvN can benefit other studies of quantum information. For instance, a direct application is algorithm design.[12] Some of the recent quantum algorithms, such as quantum learning[11] and the singular-value transformation,[27] can be described as superchannels, hence attributing their speedups properly to the resources of quantum memory. Prototypes of QvN can be realized on current quantum computers, especially with the aid of high-fidelity multiple-qubit gates.[28–30] Distinct features of QvN such as the switchability of gates and the novel type of tailed circuits can be experimentally investigated.

Our study is purely theoretical, but it also inspires the following fundamental question: would von Neumann architecture be the right choice to build real quantum computer system? Computers nowadays are designed and built with hierarchical layers of abstraction,[8,31] from gates and circuits to micro-processor, and to instruction set, operating system and software. Our recent study, including this work, provides positive answer to the question above, and it could inspire more explorations on the architecture construction of quantum computers, and also various resources to achieve quantum advantages.

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