IDH1 also had distinct clinical characteristics, including younger age and a considerably improved clinical prognosis (Table 4). It is conceivable that new treatments could be designed to take advantage of IDH1 alterations in these patients, because inhibition of a different IDH enzyme (IDH2) has recently been shown to result in increased sensitivity of tumor cells to a variety of chemotherapeutic agents (*49*). In summary, the discovery of IDH1 and other genes previously not known to play a role in human tumors (table S7) validates the utility of genome-wide genetic analysis of tumors in general and opens new avenues of basic and clinical brain tumor research.

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51. Contact information for the authors who directed the major components of this project is as follows: H. Yan, G. J. Riggins (clinical and sample coordination), yan00002@mc.duke.edu, griggin1@jhmi.edu; D. D. Bigner (pathological and clinical review), bigne001@mc.duke.edu; R. Karchin (bioinformatic analysis), karchin@jhu.edu; N. Papadopoulos (gene expression analysis), npapado1@jhmi.edu; G. Parmigiani (statistical analysis), gp@jhu.edu; B. Vogelstein, V. E. Velculescu, K. W. Kinzler (sequencing and copy number analysis), bertvog@gmail.com, velculescu@jhmi.edu, kinzlke@jhmi.edu. We thank N. Silliman, J. Ptak, L. Dobbyn, and M. Whalen for assistance with PCR amplification; D. Lister, L. J. Ehinger, D. L. Satterfield, J. D. Funkhouser, and P. Killela for assistance with DNA purification; T. Sjöblom for assistance with database management; the Agencourt sequencing team for assistance with automated sequencing; and C.-S. Liu and the SoftGenetics team for their assistance with mutation detection analyses. This project was carried out under the auspices of the Ludwig Brain Tumor Initiative and was supported by the Virginia and D. K. Ludwig Fund for Cancer Research, NIH grants CA121113, NS052507, CA43460, CA57345, CA62924, CA09547, 5P50-NS-20023, CA108786, and CA11898, the Pew Charitable Trusts, the Pediatric Brain Tumor Foundation Institute, the Hirschhorn Foundation, Alex's Lemonade Stand Foundation, the American Brain Tumor Association, the American Society of Clinical Oncology, the Brain Tumor Research Fund and Beckman Coulter Corporation. Under separate licensing agreements between the Johns Hopkins University and Genzyme, Beckman Coulter, and Exact Sciences Corporations, B.V., V.E.V., and K.W.K. are entitled to a share of royalties received by the university on sales of products related to research described in this paper. These authors and the university own Genzyme and Exact Sciences stock, which is subject to certain restrictions under university policy. The terms of these arrangements are managed by the Johns Hopkins University in accordance with its conflict-of-interest policies.

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REPORTS

Quantum Communication with Zero-Capacity Channels

Graeme Smith[1]* and Jon Yard[2]

Communication over a noisy quantum channel introduces errors in the transmission that must be corrected. A fundamental bound on quantum error correction is the quantum capacity, which quantifies the amount of quantum data that can be protected. We show theoretically that two quantum channels, each with a transmission capacity of zero, can have a nonzero capacity when used together. This unveils a rich structure in the theory of quantum communications, implying that the quantum capacity does not completely specify a channel's ability to transmit quantum information.

Noise is the enemy of all modern communication links. Cellular, Internet and satellite communications all depend crucially on active steps taken to mitigate and correct for noise. The study of communication in the presence of noise was formalized by Shannon (*1*), who simplified the analysis by making probabilistic assumptions about the nature of the noise. By modeling a noisy channel $\mathcal{N}$ as a probabilistic map from input signals to output signals, the capacity $\mathcal{C}(\mathcal{N})$ of $\mathcal{N}$ is defined as the number of bits that can be transmitted per channel use, with vanishing errors in the limit of many transmissions. This capacity is computed via the formula $\mathcal{C}(\mathcal{N}) = \max_X I(X;Y)$, where the maximization is over random variables X at the input of the channel, Y is the resulting output of the channel, and the mutual information $I(X;Y) = H(X) + H(Y) - H(X,Y)$ quantifies the correlation between input and output. $H(X) = -\sum_x p_x \log_2 p_x$ denotes the Shannon entropy, which quantifies the amount of randomness in X. The capacity, measured in bits per channel use, is the fundamental bound between communication rates that are achievable in principle and those that are not. The capacity formula guides the design of practical error-correction techniques by providing a benchmark against which engineers can test the performance of their systems. Practical implementations guided by the capacity result now come strikingly close to the Shannon limit (*2*).

A fundamental prediction of the capacity formula is that the only channels with zero capacity are precisely those for which the input and output are completely uncorrelated. Furthermore, suppose one is given simultaneous access to two noisy channels $\mathcal{N}_1$ and $\mathcal{N}_2$. The capacity of the product channel $\mathcal{N}_1 \times \mathcal{N}_2$, where the channels are used in parallel, takes the simple form $\mathcal{C}(\mathcal{N}_1 \times \mathcal{N}_2) = \mathcal{C}(\mathcal{N}_1) + \mathcal{C}(\mathcal{N}_2)$; that is, the capacity is additive. Additivity shows that capacity is an intrinsic measure of the information-conveying properties of a channel.

Quantum data are an especially delicate form of information and are particularly susceptible to the deleterious effects of noise. Because quantum communication promises to allow unconditionally secure communication (*3*), and a quantum computer could dramatically speed up some computations (*4*), there is tremendous interest in techniques to protect quantum data from noise. A quantum channel $\mathcal{N}$ models a physical process that adds noise to a quantum system via an interaction with an unobservable environment (Fig. 1), generalizing Shannon's model and enabling a more accurate depiction of the underlying physics. In this setting, it is natural to ask what the capacity of a quantum channel is for transmitting quantum-mechanical information (*5*) and whether it has a simple formula in analogy with Shannon's.

Just as any classical message can be reversibly expressed as a sequence of bits, a quantum message (that is, an arbitrary state of a given quantum system) can be reversibly transferred to a collection of two-level quantum systems, or "qubits," giving a measure of the size of the system. The goal of quantum communication is to transfer the joint state of a collection of qubits from one location to another (Fig. 2). The quantum capacity $\mathcal{Q}(\mathcal{N})$ of a quantum channel $\mathcal{N}$ is the number of qubits per channel use that can be reliably transmitted via many noisy transmissions, where each transmission is modeled by $\mathcal{N}$. Although noiseless quantum communication with a noisy quantum channel is one of the simplest and most natural communication tasks one can imagine for quantum information, it is not nearly as well understood as its classical counterpart.

An analog for mutual information in the quantum capacity has been proposed (*6*) and called the "coherent information"

$$\mathcal{Q}^{(1)}(\mathcal{N}) = \max_{\rho^A}[H(B) - H(E)] \qquad (1)$$

The entropies are measured on the states induced at the output and environment of the channel (Fig. 1) by the input state ρ^A, where $H(B)$ is the von Neumann entropy of the state ρ^B at the output. Coherent information is rather different from mutual information. This difference is closely related to the no-cloning theorem (*7*), which states that quantum information cannot be copied, because the coherent information roughly measures how much more information B holds than E. The no-cloning theorem itself is deeply tied to the fundamentally quantum concept of entanglement, in which the whole of a quantum system can be in a definite state while the states of its parts are uncertain.

The best-known expression for the quantum capacity $\mathcal{Q}$ is given (*8–10*) by the "regularization" of $\mathcal{Q}^{(1)}$: $\mathcal{Q}(\mathcal{N}) = \lim_{n\to\infty} \frac{1}{n}\mathcal{Q}^{(1)}(\mathcal{N}^{\times n})$. Here $\mathcal{N}^{\times n}$ represents the parallel use of n copies of $\mathcal{N}$. The asymptotic nature of this expression prevents one from determining the quantum capacity of a given channel in any effective way, while also making it difficult to reason about its general properties. In contrast to Shannon's capacity, where regularization is unnecessary, here it cannot be removed in general (*11*, *12*). Consequently, even apparently simple questions, such as determining from a channel's description whether it can be used to send any quantum information, are currently unresolved. We find that the answer to this question depends on context; there are pairs of zero-capacity channels that, used together, have a positive quantum capacity (Fig. 3). This shows that the quantum capacity is not additive, and thus the quantum capacity of a channel does not completely specify its capability for transmitting quantum information.

Although a complete characterization of zero-capacity channels is unknown, certain classes of zero-capacity channels are known. One class consists of channels for which the joint quantum state of the output and environment is symmetric under interchange. These symmetric channels are quite different from Shannon's zero-capacity channels, because they display correlations between the input and output. However, they are useless by themselves for quantum communication because their symmetry implies that any capacity would lead to a violation of the no-cloning theorem (*7*, *13*). Another class of zero-capacity channels is entanglement-binding channels (*14*, *15*), also called Horodecki channels, which can only produce very weakly entangled states, satisfying a condition called positive partial transposition (*16*).

Even though channels from one or the other of these classes cannot be combined to faithfully transmit quantum data, we find that when one combines a channel from each class, it is sometimes possible to obtain a positive quantum capacity. We do this by proving a new relationship between two further capacities of a quantum channel: the private capacity (*10*) and the assisted capacity (*17*).

The private capacity $\mathcal{P}(\mathcal{N})$ of a quantum channel $\mathcal{N}$ is the rate at which it can be used to send classical data that is secure against an eavesdropper with access to the environment of the channel. This capacity is closely related to quantum key distribution protocols (*3*) and was shown (*10*) to equal the regularization of the private information

$$\mathcal{P}^{(1)}(\mathcal{N}) = \max_{X,\rho_x^A}(I(X;B) - I(X;E)) \qquad (2)$$

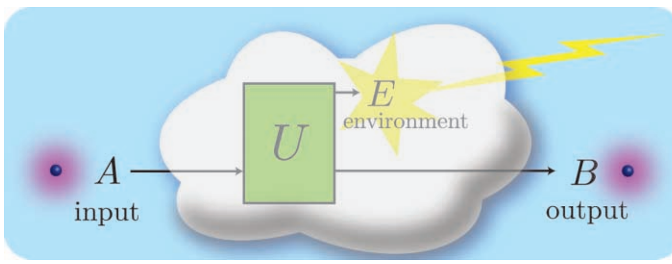

Fig. 1. Representation of a quantum channel. A channel reversibly transfers the state of a physical system in the laboratory of the sender to the combination of the system possessed by the receiver and an environment that is inaccessible to the users of the channel. Discarding the environment results in a noisy evolution of the state. The input and output denote separate places in space and/or time, modeling, for example, a leaky optical fiber or the irreversible evolution of the state of a quantum dot.

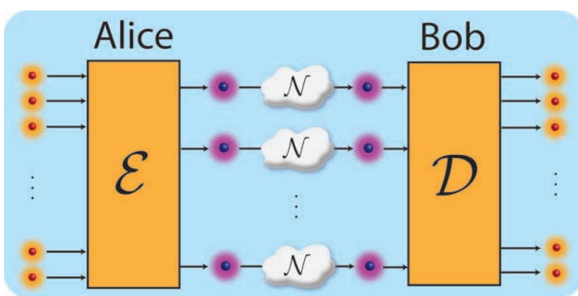

Fig. 2. The quantum capacity of a quantum channel. Quantum data are held by a sender (traditionally called Alice), who would like to transmit it to a receiver (Bob) with many parallel uses of a noisy quantum channel $\mathcal{N}$. Alice encodes the data with a collective encoding operation $\mathcal{E}$, which results in a joint quantum state on the inputs of the channels $\mathcal{N}^{\times n}$. The encoded state is sent through the noisy channels. When Bob receives the state, he applies a decoding operation $\mathcal{D}$, which acts collectively on the many outputs of the channels. After decoding, Bob holds the state that Alice wished to send. The quantum capacity is the total number of qubits in the state Alice sends divided by the number of channel uses.

[1]IBM T. J. Watson Research Center, 1101 Kitchawan Road, Yorktown Heights, NY 10598, USA. [2]Quantum Institute, Center for Nonlinear Studies (CNLS), Computer, Computational and Statistical Sciences (CCS-3), Los Alamos National Laboratory, Los Alamos, NM 87545, USA.

*To whom correspondence should be addressed. E-mail: gsbsmith@gmail.com

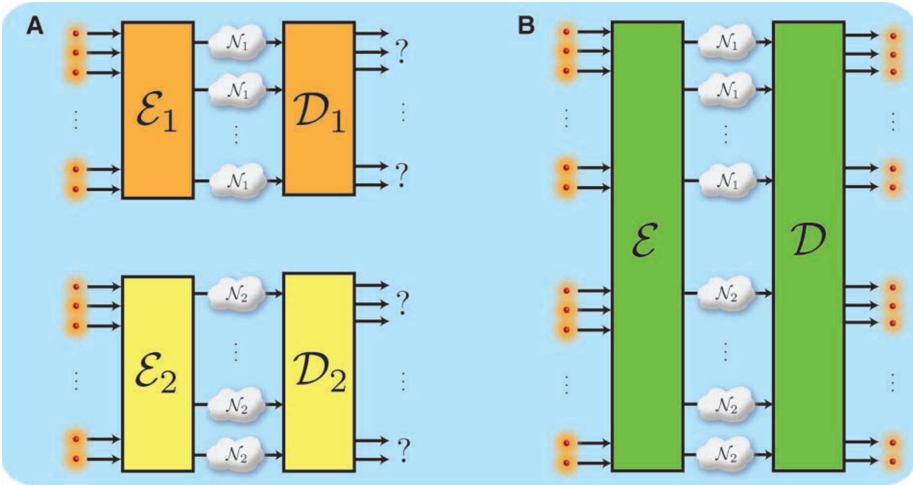

Fig. 3. (**A**) Alice and Bob attempt to separately use two zero-capacity channels $\mathcal{N}_1$ and $\mathcal{N}_2$ to transfer quantum states. Alice uses separate encoders $\mathcal{E}_1$ and $\mathcal{E}_2$ for each group of channels, and Bob uses separate decoders $\mathcal{D}_1$ and $\mathcal{D}_2$. Any attempt will fail because the capacity of each channel is zero. (**B**) The same two channels being used in parallel for the same task. Alice's encoder $\mathcal{E}$ now has simultaneous access to the inputs of all channels being used and Bob's decoding $\mathcal{D}$ is also performed jointly. Noiseless communication is nonetheless possible because $\mathcal{Q}$ is not additive.

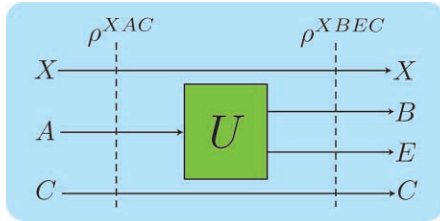

Fig. 4. Relating the private capacity and the assisted capacity. A straightforward proof of Eq. 3 uses the expression (*17*) $\mathcal{Q}_{\mathcal{A}}(\mathcal{N}) = \frac{1}{2}\max_{\rho^{XAC}}[I(X;B|C) - I(X;E|C)]$. Here, $I(X;B|C)$ is the conditional mutual information: $H(XC) + H(BC) - H(XBC) - H(C)$. It is evaluated on the state obtained by putting the $\mathcal{A}$ part of a state ρ^{XAC} into the channel $\mathcal{N}$, which can be thought of as mapping $A \rightarrow BE$ as in Fig. 2. The maximization here is similar in form to Eq. 2, but is over a less-constrained type of state. Therefore, $\frac{1}{2}\mathcal{P}^{(1)}(\mathcal{N}) \leq \mathcal{Q}_{\mathcal{A}}(\mathcal{N})$. This bound holds for the associated regularized quantities, and because regularization does not change $\mathcal{Q}_{\mathcal{A}}$, Eq. 3 follows.

where the maximization is over classical random variables X and quantum states ρ_x^A on the input of $\mathcal{N}$ depending on the value x of X.

In order to find upper bounds on the quantum capacity, an "assisted capacity" was recently introduced (*17*), in which one allows the free use of arbitrary symmetric channels to assist quantum communication over a given channel. Letting $\mathcal{A}$ denote a symmetric channel of unbounded dimension (the strongest such channel), the assisted capacity $\mathcal{Q}_{\mathcal{A}}(\mathcal{N})$ of a quantum channel $\mathcal{N}$ satisfies (*17*) $\mathcal{Q}_{\mathcal{A}}(\mathcal{N}) = \mathcal{Q}(\mathcal{N} \times \mathcal{A}) = \mathcal{Q}^{(1)}(\mathcal{N} \times \mathcal{A})$.

Because the dimension of the input to $\mathcal{A}$ is unbounded, we cannot evaluate the assisted capacity in general. Nonetheless, the assisted capacity helps to reason about finite-dimensional channels.

Although Horodecki channels have zero quantum capacity, examples of such channels with nonzero private capacity are known (*18*, *19*). One of the two zero-capacity channels we will combine to give positive joint capacity is such a private Horodecki channel $\mathcal{N}_{\mathrm{H}}$ and the other is the symmetric channel $\mathcal{A}$. Our key tool is the following new relationship between the capacities of any channel $\mathcal{N}$ (Fig. 4)

$$\frac{1}{2}\mathcal{P}(\mathcal{N}) \leq \mathcal{Q}_{\mathcal{A}}(\mathcal{N}) \quad (3)$$

A channel's assisted capacity is at least as large as half its private capacity. It follows that any private Horodecki channel $\mathcal{N}_{\mathrm{H}}$ has a positive assisted capacity, and thus the two zero-capacity channels $\mathcal{N}_{\mathrm{H}}$ and $\mathcal{A}$ satisfy $\mathcal{Q}_{\mathcal{A}}(\mathcal{N}_{\mathrm{H}}) = \mathcal{Q}(\mathcal{N}_{\mathrm{H}} \times \mathcal{A}) > 0$.

Although our construction involves systems of unbounded dimension, one can show that any private Horodecki channel can be combined with a finite symmetric channel to give positive quantum capacity. In particular, there is a private Horodecki channel acting on a four-level system (*19*). This channel gives positive quantum capacity when combined with a small symmetric channel—a 50% erasure channel $\mathcal{A}_e$ with a four-level input, which half of the time delivers the input state to the output, otherwise telling the receiver that an erasure has occurred. We show (*20*) that the parallel combination of these channels has a quantum capacity greater than 0.01.

We find this "superactivation" to be a startling effect. One would think that the question, "can this communication link transmit any information?" would have a straightforward answer. However, with quantum data, the answer may well be "it depends on the context." Taken separately, private Horodecki channels and symmetric channels are useless for transmitting quantum information, albeit for entirely different reasons. Nonetheless, each channel has the potential to activate the other, effectively canceling the other's reason for having zero capacity. We know of no analog of this effect in the classical theory. Perhaps each channel transfers some different but complementary kind of quantum information. If so, can these kinds of information be quantified in an operationally meaningful way? Are there other pairs of zero-capacity channels displaying this effect? Are there triples? Does the private capacity also display superactivation? Can all Horodecki channels be superactivated, or just those with positive private capacity? What new insights does this yield for computing the quantum capacity in general?

Besides additivity, our findings resolve two open questions about the quantum capacity. First we find (*20*) that the quantum capacity is not a convex function of the channel. Convexity of a capacity means that a probabilistic mixture of two channels never has a higher capacity than the corresponding average of the capacities of the individual channels. Violation of convexity leads to a counterintuitive situation in which it can be beneficial to forget which channel is being used. We also find (*20*) channels with an arbitrarily large gap between $\mathcal{Q}^{(1)}$ [the so-called "hashing rate" (*8*–*10*)] and the quantum capacity. It had been consistent with previous results (*11*, *12*) to believe that $\mathcal{Q}$ and $\mathcal{Q}^{(1)}$ would be equal up to small corrections. Our work shows that this is not the case and indicates that the hashing rate is an overly pessimistic benchmark against which to measure the performance of practical error-correction schemes. This could be good news for the analysis of fault-tolerant quantum computation in the very noisy regime.

Forms of this sort of superactivation are known in the multiparty setting, where several separated parties communicate via a quantum channel with multiple inputs or outputs (*21*–*24*), and have been conjectured for a quantum channel assisted by classical communication between the sender and receiver (*25*, *26*). Because these settings are rather complex, it is perhaps unsurprising to find exotic behavior. In contrast, the problem of noiseless quantum communication with a noisy quantum channel is one of the simplest and most natural communication tasks imaginable in a quantum-mechanical context. Our findings uncover a level of complexity in this simple problem that had not been anticipated and point toward several fundamentally new questions about information and communication in the physical world.

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Synthesis and Solid-State NMR Structural Characterization of ^{13}C-Labeled Graphite Oxide

Weiwei Cai,[1,2] Richard D. Piner,[1] Frank J. Stadermann,[3] Sungjin Park,[1] Medhat A. Shaibat,[4] Yoshitaka Ishii,[4] Dongxing Yang,[1] Aruna Velamakanni,[1] Sung Jin An,[5] Meryl Stoller,[1] Jinho An,[1] Dongmin Chen,[2] Rodney S. Ruoff[1]*

The detailed chemical structure of graphite oxide (GO), a layered material prepared from graphite almost 150 years ago and a precursor to chemically modified graphenes, has not been previously resolved because of the pseudo-random chemical functionalization of each layer, as well as variations in exact composition. Carbon-13 (^{13}C) solid-state nuclear magnetic resonance (SSNMR) spectra of GO for natural abundance ^{13}C have poor signal-to-noise ratios. Approximately 100% ^{13}C-labeled graphite was made and converted to ^{13}C-labeled GO, and ^{13}C SSNMR was used to reveal details of the chemical bonding network, including the chemical groups and their connections. Carbon-13–labeled graphite can be used to prepare chemically modified graphenes for ^{13}C SSNMR analysis with enhanced sensitivity and for fundamental studies of ^{13}C-labeled graphite and graphene.

Unlike crystalline materials, the structure of materials that are amorphous or that vary in chemical composition can be difficult to determine. Solid-state nuclear magnetic resonance (SSNMR) can provide important structural insights, but often requires very high enrichment of nuclei with NMR-active spins. One example of such a material that has proven difficult to characterize, despite having been first prepared almost 150 years ago (*1*), is graphite oxide (GO), which can be prepared by heating graphite in oxidizing chemicals. GO is a layered material containing interlamellar water. Materials derived from GO include its chemically functionalized (*2*), reduced (*3*), and thermally expanded forms (*4*), as well as chemically modified graphenes (*2*, *3*, *5*–*8*).

SSNMR has been done on GO but has not provided a complete understanding of the chemical structure of this material, although the detailed chemical structure has been actively researched for many years (*2*, *7*). One difficulty is that the spectra do not attain a high signal-to-noise (S/N) ratio for natural abundance ^{13}C. The lack of ^{13}C-labeled GO has prevented application of modern multidimensional SSNMR methods that can provide information on the bonding arrangements of atoms and their connectivities. Although a series of one-dimensional (1D) ^{13}C SSNMR studies for GO and reduced GO revealed signal assignments and the basic chemical compositions of each, there is sparse experimental evidence of the connectivities of the chemical groups such as sp^2-bonded carbons (C=C), epoxide, carbonyl, and carboxylic groups. Thus, a variety of structural models of GO are still debated (*2*). However, we found from Monte Carlo simulations that even at only 20% ^{13}C, the abundance of ^{13}C-^{13}C bonds will be 400 times that of an unlabeled sample, so that the time required for detecting ^{13}C-^{13}C pairs in SSNMR of such a

[1]Department of Mechanical Engineering and the Texas Materials Institute, University of Texas at Austin, Austin, TX 78712, USA. [2]Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100080, China. [3]Laboratory for Space Sciences, Department of Physics, Washington University, St. Louis, MO 63130, USA. [4]Department of Chemistry, University of Illinois at Chicago, 845 West Taylor Street, Chicago, IL 60607, USA. [5]National Creative Research Initiative Center for Semiconductor Nanorods and Department of Materials Science and Engineering, Pohang University of Science and Technology, Pohang, Gyeongbuk 790-784, Korea.

*To whom correspondence should be addressed. E-mail: r.ruoff@mail.utexas.edu

Fig. 1. (**A**) Optical images of Ni, and SEM images of (**B**) ^{13}C-labeled synthetic graphite and (**C**) the wrinkles.

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Quantum Communication with Zero-Capacity Channels

Graeme Smith and Jon Yard

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