

Degenerate Quantum Codes for Pauli Channels

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A striking feature of quantum error correcting codes is that they can sometimes be used to correct more errors than they can uniquely identify. Such *degenerate* codes have long been known, but have remained poorly understood. We provide a heuristic for designing degenerate quantum codes for high noise rates, which is applied to generate codes that can be used to communicate over almost any Pauli channel at rates that are impossible for a nondegenerate code. The gap between nondegenerate and degenerate code performance is quite large, in contrast to the tiny magnitude of the only previous demonstration of this effect. We also identify a channel for which none of our codes outperform the best nondegenerate code and show that it is nevertheless quite unlike any channel for which nondegenerate codes are known to be optimal.

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It was Shannon [1] who discovered, by a random coding argument, the beautiful fact that the capacity of a noisy channel \mathcal{N} is equal to the maximal mutual information between an input variable, X , and its image under the action of the channel:

$$C = \max_X I(X; \mathcal{N}(X)). \quad (1)$$

It is remarkable that this maximization is over a single input to the channel; it does not require consideration of inputs correlated over many channel uses.

One would hope that, as in the classical case, there is some measure of quantum correlations that can be maximized over inputs to a quantum channel to give the capacity. Unfortunately, this appears not to be the case. The natural generalization of Eq. (1) is to replace the random variable X with a quantum state ρ and the mutual information with the *coherent information* I^c giving

$$Q_1 = \max_{\rho} I^c(\mathcal{N}, \rho), \quad (2)$$

where

$$I^c(\mathcal{N}, \rho) = I(I \otimes \mathcal{N}(|\phi^{AB}\rangle\langle\phi^{AB}|)). \quad (3)$$

Here $|\phi_{AB}\rangle$ is a purification of ρ . Its use reflects the fact that unlike in the classical case, there can be no remaining copy of the channel input with which to compare correlations—instead we must consider the quantum state as a whole. The coherent information is defined by $I^c(\rho_{AB}) = S(\rho_B) - S(\rho_{AB})$ with $S(\rho) = -\text{Tr}(\rho \log \rho)$.

While we can achieve Q_1 using a random code on the typical subspace of the maximizing ρ , it has long been known that this rate is not always optimal [2,3]. They exhibit codes with rates larger than Q_1 for very noisy depolarizing channels which have Q_1 small or even zero.

The correct quantum capacity formula is not Q_1 , but instead is given by [4–6]

$$Q = \lim_{n \rightarrow \infty} \frac{1}{n} \max_{\rho_n} I^c(\mathcal{N}^{\otimes n}, \rho_n), \quad (4)$$

where taking the limit $n \rightarrow \infty$ means that we must consider the behavior of the channel on inputs entangled across many uses. This *multiletter* formula is an expression of our ignorance about the structure of capacity achieving codes for a quantum channel.

The difference between these single- and multiletter formulas is intimately related to the existence of degenerate quantum codes. Strictly speaking, degeneracy is not a property of a quantum code alone, but a property of a code together with a family of errors it is designed to correct. More formally, one usually says that a code \mathcal{C} degenerately corrects a set of errors \mathcal{E} if in addition to correcting \mathcal{E} , there are multiple errors in \mathcal{E} that are mapped to the same error syndrome. In the context of probabilistic noise, which we will be concerned with exclusively, we say that a code \mathcal{C} degenerately corrects the noise due to a channel \mathcal{N} if it can be decoded with a high fidelity and furthermore multiple errors in the set of typical errors of \mathcal{N} are mapped to the same error syndrome. For the most part, we will be concerned with *grossly degenerate* codes, which have the further property that the number of typical errors mapped to each syndrome is exponential in the code's block length.

For the depolarizing channel considered in [2,3], as well as the Pauli channels considered below, Q_1 is exactly the maximum rate achievable with a nondegenerate code. That $Q > Q_1$ is then established by the construction of a massively degenerate code. While this was accomplished in the work of [2,3], the difference found was over a minuscule range of noise parameters and extremely small in magnitude. As a result, one may have thought that Eq. (2) is “essentially correct”, with some minor modifications in the very noisy regime. In the decade since the appearance of these two works, there has been almost no progress on understanding the difference between the single- and multiletter expressions above, a failure which has to some extent been tempered by the hope that the smallness of the effect would make it amenable to a perturbative analysis. We will show that this cannot be the case and in fact

that the smallness of the effect found in [2,3] is more accidental than fundamental.

Until now, very little has been understood about why the degenerate codes of [2,3] work, besides that they seem to be highly degenerate. The main contribution of this Letter is to provide a conceptual explanation of why degenerate codes of this type work, along with a related heuristic for designing codes for more general channels. Using this heuristic, we find better codes for almost all Pauli channels, and exhibit cases where the effect of degeneracy can be quite large. This large gap between the performance of nondegenerate and degenerate codes implies that a perturbative approach to is unlikely to be useful.

A secondary contribution we believe to be no less important, but which lies on the periphery of the current work, is the identification of the two-Pauli channel as an important piece of the degenerate coding puzzle. This channel derives no benefit from the degenerate codes we study, but is also quite different from any of the degradable channels, a set of channels including the dephasing and erasure channels, and comprising the only channels for which nondegenerate codes are known to be optimal [7]. Therefore, either there is some other sort of degenerate code that *will* beat Q_1 or Q_1 can be optimal for nondegradable channels. Either outcome seems plausible, and progress on resolving this dichotomy would necessarily deepen our understanding of the quantum coding problem in general. Along a similar line, we have introduced a general method for showing that a channel is not degradable, taking one of the first steps in the program to classify all degradable channels.

Cat codes for Pauli channels.—The codes we will consider are m -qubit repetition codes, sometimes called “cat codes” because the code space is spanned by $|0\rangle^{\otimes m}$ and $|1\rangle^{\otimes m}$. These have stabilizers $Z_1Z_2, Z_1Z_3, \dots, Z_1Z_m$ and logical operators $\bar{X} = X^{\otimes m}$ and $\bar{Z} = Z_1$, so that an error of the form X^uZ^v leads to syndrome $\{u_1 \oplus u_2, \dots, u_1 \oplus u_m\}$ and in the absence of a recovery operation gives a logical error of $\bar{X}^{u_1}\bar{Z}^{\oplus v_i}$. By encoding half of $|\phi^+\rangle_{AB} = (|00\rangle + |11\rangle)/\sqrt{2}$ in our repetition code, we get the state for which the coherent information in Eq. (4) will be more than m times Q_1 . Sending the B system of the resulting $|\phi_m^+\rangle_{AB}$ through $\mathcal{N}_p^{\otimes m}$ and, subsequently, measuring the stabilizers $\{Z_1Z_l\}_{l=2}^m$ leads to the state $\rho_{AB_m} = \sum_{\mathbf{r} \in \{0,1\}^{m-1}} \Pr(\mathbf{r}) I \otimes \mathcal{N}^{\mathbf{r}}(|\phi^+\rangle\langle\phi^+|) \otimes |\mathbf{r}\rangle\langle\mathbf{r}|$, where \mathbf{r} is the syndrome measured, $\mathcal{N}^{\mathbf{r}}$ is the induced channel given \mathbf{r} (which is also a Pauli channel), and $\Pr(\mathbf{r})$ is the probability of measuring \mathbf{r} . Concatenating our repetition code with a random stabilizer code allows communication with high fidelity at a rate of

$$\frac{1}{m} I^c(\rho_{AB_m}) = \frac{1}{m} \sum_{\mathbf{r}} \Pr(\mathbf{r}) I^c(I \otimes \mathcal{N}^{\mathbf{r}}(|\phi^+\rangle\langle\phi^+|)). \quad (5)$$

Because the repetition code is highly symmetric we can find explicit formulas for both $\Pr(\mathbf{r})$ and $\mathcal{N}^{\mathbf{r}}$, and thus a fairly compact expression for $I^c(\rho_{AB_m})$. The joint proba-

bilities of logical errors and syndrome outcomes are

$$\begin{aligned} \Pr(\bar{X}^u\bar{Z}^v, \mathbf{r}) &= \frac{1}{2} ((p_x + p_y)^{u(m-2r)+r} \\ &\quad \times (1 - p_x - p_y)^{(1-u)(m-2r)+r} \\ &\quad + (-1)^v (p_x - p_y)^{u(m-2r)+r} \\ &\quad \times (1 - p_x - p_y - 2p_z)^{(1-u)(m-2r)+r}), \quad (6) \end{aligned}$$

where $r = |\mathbf{r}|$, the Hamming weight of \mathbf{r} . Equation (6) allows us to find both $\Pr(\mathbf{r})$ and the error probabilities of the induced channels $\mathcal{N}^{\mathbf{r}}$. This formula depends on r but has no other dependence on \mathbf{r} , which dramatically reduces the number of induced channels that need to be considered.

By evaluating (5) on the probabilities of (6), we find that for almost all Pauli channels there is a repetition code with nonzero rate at the hashing point. When $p_x \gg p_z$ the best code is in the Z basis with length scaling like $1/p_z$, which we will study in detail in the next section. For $p_x \geq p_z \geq p_y$, it is a good rule of thumb to use a Z repetition code of length $m \approx 1/p_z$, with the largest increase in rate for fairly asymmetrical channels (Fig. 1).

Repetition lengths for almost bitflip channels.—To illustrate the tradeoff determining the best repetition code length, we will study their performance for channels with independent phase and amplitude error probabilities. An error X^uZ^v is said to be a phase error if $v = 1$ and an amplitude error if $u = 1$ (note that when $u = 1$ and $v = 1$ it is both). Throughout, we define $q_x = p_x + p_y$ and $q_z = p_z + p_y$ to be the amplitude and phase error probabilities, respectively, and in a slight abuse of terminology refer to amplitude and phase errors as X and Z errors, with a Y error being “both X and Z .” Independence of phase and amplitude errors requires $p_x = q_x(1 - q_z)$, $p_y = q_xq_z$, and

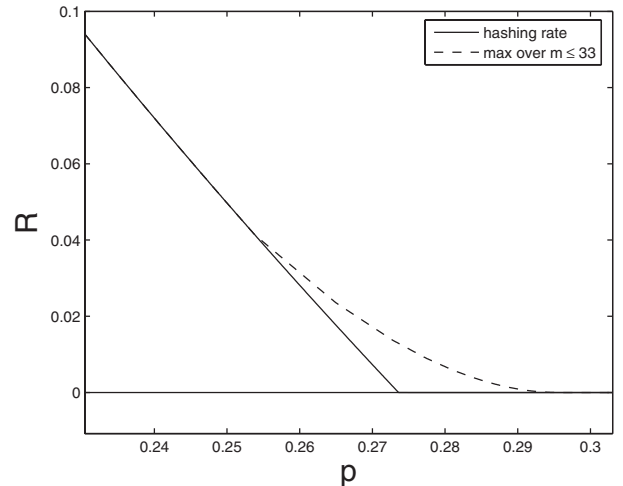


FIG. 1. Best Z -cat code rates for independent phase and amplitude errors with $q_z/q_x = (p_z + p_y)/(p_x + p_y) = 9$ (and where $p = p_x + p_y + p_z$). The optimal m increases with p . $m = 33$ gives the best threshold of ≈ 0.295 , compared to a hashing threshold less than 0.274. The rule of thumb $m \approx 1/p_z$ gives an estimated $m = 36$, not far from the optimum.

$p_z = q_z(1 - q_x)$. When $q_x \gg q_z$ we find that the repetition code with the best zero-rate noise threshold has $m \approx 1/q_z$, which can be understood by considering the effective channels induced by the code.

The independence of phase and amplitude, together with our generators involving only Z 's tells us that the probability of a logical phase error is independent of \mathbf{r} , and given by $q_{\bar{z}} = \Pr(\bigoplus_{l=1}^m v_l = 1) = [1 - (1 - 2q_z)^m]/2$, which also follows from Eq. (6).

As we have already seen, the probability of a logical amplitude error depends only on $r = |\mathbf{r}|$, not on \mathbf{r} itself. If m is large, the probability distribution of r becomes concentrated near $r_o \equiv (m - 1)q_x$ and $r_1 \equiv (m - 1)(1 - q_x)$. This is because there are typically $(m - 1)q_x$ X errors on qubits 2 through m and these qubits all get flipped if qubit 1 has an X error. So, the measured value of r tells us whether or not a logical X error has occurred, at least with high probability. One can see from this, together with the $q_{\bar{z}}$ above, that as m increases we learn more about the logical X error at the expense of knowing less about the logical Z .

Indeed, the optimal repetition length will minimize the entropy in the logical qubits conditioned on r , which near the hashing point occurs when the repetition length is around $1/q_z$, at which point almost all of the X entropy has been removed. If we increase m beyond this the gain in information about the logical X is less than the resulting decrease in our knowledge of the logical Z 's. The overall rate thus achieved at the hashing point is $2q_z \ln(1/q_z) / \ln \ln(1/q_z)$.

Note that essentially all of the entropy in the X errors is removed by the best code, with the optimal length determined by a tradeoff between the reduction of entropy in the X errors and the increase of entropy in the Z errors. This sort of tradeoff also determines the optimal repetition code length for a general Pauli channel.

Concatenated repetition codes.—We can immediately apply this analysis to design even better codes by using concatenation. By adapting a second level of repetition code to the error probabilities of the channels induced by the first level we can exceed the performance of any single level cat code. We have used this approach for the depolarizing channel with the results shown in Fig. 2, where we plot the probabilities at which the rate of a concatenated 3 in m and 5 in m code goes to zero as a function of m , the size of the outer cat code. If we first use a 3-cat code in the Z basis, followed by an m -cat code in the X basis, we find the highest threshold for a 3 in 19 code, with a nonzero rate up to $p \approx 0.19086$, surpassing the codes of [3]. Starting with a 5-cat code the threshold increases up to $p \approx 0.19088$ for $m = 16$, the best known code for this channel, but for higher values of m the computation of this probability is quite slow. Based on the character of the channels induced by the inner repetition code, together with the behavior for $m \leq 16$ we expect that the threshold increases until something like 5 in 25, at which point a larger m begins to reduce the effectiveness of the code.

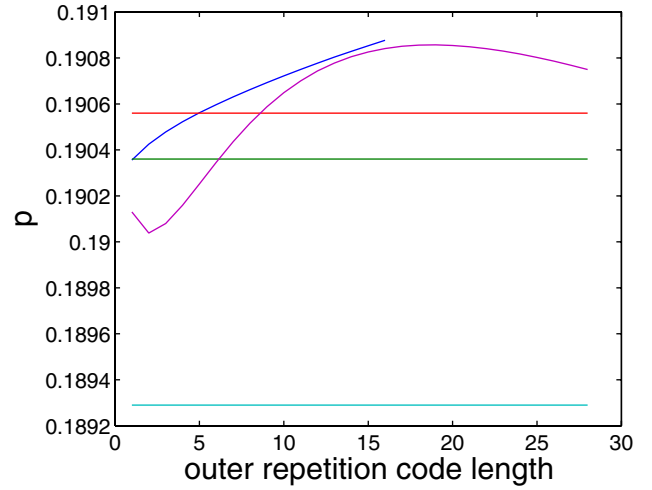


FIG. 2 (color online). Error probability where the rate goes to zero, as a function of length of second level cat code. Here the horizontal axis is m , the length of the second level cat code. The bottom line is hashing, the middle line is a 5 qubit repetition code, the upper line is a concatenated 5 in 5 repetition code. The lower curve is a 3 in m repetition code; the upper is 5 in m .

Two-Pauli channels are special.—Besides the one-Pauli channels, the only channels for which we can find no code offering an advantage near the hashing point are tightly concentrated near $\mathcal{N}_p^{\text{tp}}(\rho) \equiv (1 - p)\rho + \frac{p}{2}X\rho X + \frac{p}{2}Z\rho Z$. While hashing is optimal for one-Pauli channels [8], $\mathcal{N}_p^{\text{tp}}$ is not known to have additive coherent information, which is equivalent to the optimality of hashing. Furthermore, we will show that unlike all channels known to be additive this channel is not degradable [7].

Every channel \mathcal{N} can be expressed as an isometry followed by a partial trace, which is to say there is an isometry $U_{\mathcal{N}}: A \rightarrow BE$ such that $\mathcal{N}(\rho) = \text{Tr}_E U_{\mathcal{N}} \rho U_{\mathcal{N}}^\dagger$. The complementary channel of \mathcal{N} , called \mathcal{N}^C , results by tracing out system B rather than E : $\mathcal{N}^C(\rho) = \text{Tr}_B U_{\mathcal{N}} \rho U_{\mathcal{N}}^\dagger$. A channel is called degradable if there is a completely positive map, $\mathcal{D}: B \rightarrow E$, which “degrades” \mathcal{N} to \mathcal{N}^C , so that $\mathcal{D} \circ \mathcal{N} = \mathcal{N}^C$. The existence of such a map immediately implies the additivity of I^c [7], which can be seen by noting that $I^c(\mathcal{N}^{\otimes(n_1+n_2)}, \rho_{n_1 n_2}) \leq I^c(\mathcal{N}^{\otimes n_1}, \rho_{n_1}) + I^c(\mathcal{N}^{\otimes n_2}, \rho_{n_2})$ exactly when $I(E_{n_1}; E_{n_2}) \leq I(B_{n_1}; B_{n_2})$ and recalling that $I(B_{n_1}; B_{n_2})$ cannot increase under local operations. We now show there is no such \mathcal{D} for $\mathcal{N}_p^{\text{tp}}$ when $0 < p < 1$.

Letting $\mathcal{N}_p^{\text{tp}}(|i\rangle\langle j|) = \sum_{kl} N_{ij;kl} |k\rangle\langle l|$ define N and $\mathcal{N}_p^{\text{tp}C}(|i\rangle\langle j|) = \sum_{kl} N_{ij;kl}^C |k\rangle\langle l|$ define N^C , we find

$$N = \begin{pmatrix} 1-p/2 & 0 & 0 & p/2 \\ 0 & 1-3p/2 & p/2 & 0 \\ 0 & p/2 & 1-3p/2 & 0 \\ p/2 & 0 & 0 & 1-p/2 \end{pmatrix} \text{ and}$$

$$N^C = \begin{pmatrix} p/2 & 0 & 0 & 0 & p/2 & \alpha & 0 & \alpha & 1-p \\ 0 & -p/2 & \alpha & p/2 & 0 & 0 & \alpha & 0 & 0 \\ 0 & p/2 & \alpha & -p/2 & 0 & 0 & \alpha & 0 & 0 \\ p/2 & 0 & 0 & 0 & p/2 & -\alpha & 0 & -\alpha & 1-p \end{pmatrix},$$

where $\alpha = \sqrt{p(1-p)}/2$. If $\mathcal{N}_p^{\text{tp}}$ is degradable, there must be a CPTP map \mathcal{D} such that $\mathcal{D} \circ \mathcal{N} = \mathcal{N}^C$, which is equivalent to $ND = N^C$, with D defined by $\mathcal{D}(|s\rangle\langle t|) = \sum_{uv} D_{st;uv} |u\rangle\langle v|$. For N and N^C as above, this gives

$$D = \begin{pmatrix} p/2 & 0 & 0 & 0 & p/2 & \beta & 0 & \beta & 1-p \\ 0 & -\gamma & \beta & \gamma & 0 & 0 & \beta & 0 & 0 \\ 0 & \gamma & -\beta & \gamma & 0 & 0 & \beta & 0 & 0 \\ p/2 & 0 & 0 & 0 & p/2 & -\beta & 0 & -\beta & 1-p \end{pmatrix}$$

with $\beta = \sqrt{p(2-2p)}$ and $\gamma = p/(2-4p)$. The Choi matrix [9] of \mathcal{D} , $C_{ik,jl}^{\mathcal{D}} = D_{ij,kl}$, is thus

$$C^{\mathcal{D}} = \begin{pmatrix} p/2 & 0 & 0 & 0 & -\gamma & \beta \\ 0 & p/2 & \beta & \gamma & 0 & 0 \\ 0 & \beta & 1-p & \beta & 0 & 0 \\ 0 & \gamma & \beta & p/2 & 0 & 0 \\ -\gamma & 0 & 0 & 0 & p/2 & -\beta \\ \beta & 0 & 0 & 0 & -\beta & 1-p \end{pmatrix}$$

which contains the subblock

$$\begin{pmatrix} p/2 & -\gamma \\ -\gamma & p/2 \end{pmatrix}.$$

This has a negative eigenvalue for all $0 < p < 1$, so that $C^{\mathcal{D}}$ cannot be nonnegative and thus \mathcal{D} is not CP.

Besides repetition codes, we have explored concatenated repetition codes for $\mathcal{N}_p^{\text{tp}}$, all of which performed worse than the hashing rate of $1 - H(p) - p$. This suggests the capacity of $\mathcal{N}_p^{\text{tp}}$ is exactly $1 - H(p) - p$, and in light of its nondegradability we hope a proof of this conjecture will point towards a new sufficient criterion for the additivity of coherent information.

Discussion.—It is tempting to ask if there is a simpler characterization of the quantum channel capacity than is provided by Eq. (4). In particular, contrary to what is sometimes claimed, the results of [2,3] and this work do not rule out a single letter formula for the capacity—what is ruled out is the possibility that the single letter optimized coherent information is the correct formula. It could be that there *is* a single letter formula for the capacity, or less ambitiously simply an efficiently calculable expression, which takes degeneracy into account. The characterization of capacity in terms of coherent information is fundamentally nondegenerate, and it may be this which leads to the necessity of regularization, rather than an inherent superadditivity of quantum information.

More concretely, the two-Pauli channel with equal probabilities seems to be somehow different from other Pauli channels. Given their success with almost all other Pauli channels, the failure of cat codes to beat Q_1 in this case suggests that hashing is optimal. Resolving this conjecture seems to be a manageable problem whose solution may lead to a better understanding of additivity questions for quantum channels in general.

The ideas explored here are also useful for quantum key distribution. In particular, using highly structured codes for information reconciliation improves the noise threshold of BB84 with one-way classical post processing from 12.4% to 12.9% [10].

Finally, we hope the coding approach suggested by the almost bitflip channel will lead to codes with rates beyond what we have presented here. Focusing on reducing the amplitude error rate with an inner code while trying to avoid scrambling the phase errors more than necessary and following this up with a random stabilizer code (or perhaps a second similarly chosen code reversing the roles of amplitude and phase) offers an appealing heuristic for code design. Viewed in this way, the inner codes we have considered are quite primitive—a repetition code is the simplest code there is—and it seems likely more sophisticated codes will perform better.

In summary, we have provided a toolset for studying degenerate codes on Pauli channels. We have demonstrated channels and codes for which the gap between the degenerate and nondegenerate performance is quite large compared to previous results, and improved the threshold for the more generally applicable depolarizing channel. Whether the capacity of the two-Pauli channel can be improved by degenerate codes remains an open question whose solution will likely prove illuminating.

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