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Parity- and Time-Reversal-Violating Form Factors of the Deuteron

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We calculate the electric-dipole and magnetic-quadrupole form factors of the deuteron that arise as a low-energy manifestation of parity and time-reversal violation in quark-gluon interactions. We consider the QCD vacuum angle and the dimension-six operators that originate from physics beyond the Standard Model: the quark electric and chromo-electric dipole moments, and the gluon chromo-electric dipole moment. Within the framework of two-flavor chiral perturbation theory, we show that in combination with the nucleon electric dipole moment, the deuteron moments would allow an identification of the dominant source(s) of symmetry violation.

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Permanent electric dipole moments (EDMs) of particles, nuclei, atoms, and molecules violate both parity (P) and time-reversal (T), or equivalently CP, invariance [1]. Since CP violation due to quark mixing in the electroweak sector of the Standard Model (SM) seems insufficient to explain the observed matter-antimatter asymmetry in the universe [2] and predicts immeasurably small values for the EDMs of nucleons and nuclei [3], searches for nonzero EDMs are an excellent probe for new sources of CP violation. Experiments with ultracold neutrons are in preparation that aim to improve the bound on the neutron EDM [4] by two orders of magnitude [5]. Moreover, plans exist to measure the EDMs of light ions, in particular the proton and the deuteron, in storage ring experiments at similar levels of accuracy [6]. The current generation of ongoing and planned EDM experiments probes the same energy scales as the LHC, and there are strong expectations that nonzero results will soon be found.

An outstanding theoretical issue is to identify the fundamental CP-violating mechanisms, and in particular to relate a positive signal in the EDM experiments to the P- and T-violating ($\not{P}\not{T}$) sources at the quark-gluon level. The SM contains the $\not{P}\not{T}$ QCD $\bar{\theta}$ term [7], which has dimension four and would be expected to give the main contribution to hadronic $\not{P}\not{T}$. However, since the experimental upper limit on the neutron EDM constrains $\bar{\theta}$ to be unnaturally small [8], $\bar{\theta} \lesssim 10^{-10}$, possible contributions from higher-dimensional $\not{P}\not{T}$ sources can be relevant, or even dominant. These higher-dimensional operators have their origin beyond the SM, in an ultraviolet complete theory at a high energy scale $M_{\not{T}}$, for example a supersymmetric version of the SM [9]. The first such effective $\not{P}\not{T}$ operators one encounters have dimension six [10, 11], *viz.* the quark EDM (qEDM) and the quark and gluon chromo-electric dipole moments (qCEDM and gCEDM). We show that in combination with the nucleon EDM, a measurement of the deuteron $\not{P}\not{T}$ form factors (FFs) would allow the disentanglement of these $\not{P}\not{T}$ sources.

The difficulty in calculating such low-energy observables stems from the breakdown of perturbation theory in the QCD coupling constant below the characteristic QCD scale $M_{\rm QCD} \sim 2\pi F_\pi \simeq 1.2$ GeV, with $F_\pi = 185$ MeV the pion decay constant. For processes at momenta $Q \sim m_\pi$, the mass of the lightest hadron, the pion, we can nevertheless express observables in a controlled expansion in powers of Q using chiral perturbation theory (ChPT) [12] with the two lightest quark flavors u and d. This effective field theory (EFT) involving pions, nucleons and photons correctly incorporates the (approximate) symmetries of QCD, in particular the spontaneously and explicitly broken $SO(4)$ chiral symmetry, and describes low-energy physics in a model-independent way. All effective hadronic interactions that transform under symmetries as terms in the QCD Lagrangian are allowed, each one being associated with a parameter, or low-energy constant (LEC), which can be estimated using naive dimensional analysis (NDA) [11, 13]. Since the $\not{P}\not{T}$ sources break chiral symmetry in different ways [14], they can in principle be distinguished by the form and expected strength of their hadronic interactions.

The nucleon EDFF partially reflects the $\not{P}\not{T}$ source at the quark-gluon level [15–17]: a measurement of the nucleon EDM and its Schiff moment [18] could distinguish between $\not{P}\not{T}$ originating from the $\bar{\theta}$ term or qCEDM on the one hand, and the qEDM or gCEDM on the other. Since also the deuteron can be analyzed with firm theoretical tools, we focus here on its $\not{P}\not{T}$ electromagnetic FFs which, part from small relativistic corrections, are defined from the $\not{P}\not{T}$ part of the electromagnetic current, $J^\mu_{\not{P}\not{T}}$, by

$$\langle \vec{p}\,', j | J^0_{\not{P}\not{T}} | \vec{p}, i\rangle = -\epsilon^{ijl} q^l F_D(\vec{q}\,^2), \tag{1}$$

$$\langle \vec{p}\,', j | J^k_{\not{P}\not{T}} | \vec{p}, i\rangle = -\epsilon^{mnl} q^l \left[\delta^{mi}\delta^{nj} K^k \frac{F_D(\vec{q}\,^2)}{m_d} - \frac{1}{4}\delta^{mk}(\delta^{ni}q^j + \delta^{nj}q^i) F_M(\vec{q}\,^2)\right], \tag{2}$$

where $|\vec{p}, i\rangle$ denotes a deuteron state of momentum $\vec{p}$ and polarization δ^μ_i in the rest frame, normalized so that $\langle \vec{p}\,', j|\vec{p}, i\rangle = \sqrt{1+\vec{p}\,^2/m_d^2}(2\pi)^3\delta^{(3)}(\vec{q})\delta_{ij}$, $\vec{q} = \vec{p} - \vec{p}\,'$ is the photon momentum, $\vec{K} = (\vec{p}\,' + \vec{p})/2$, and $m_d =$

$2m_N - \gamma^2/m_N + \ldots$ is the deuteron mass in terms of the nucleon mass m_N and the binding momentum γ. We show that a combination of the deuteron EDM, $d_d = F_D(0)$, and nucleon EDM can separate the qCEDM from the other $\not{P}\not{T}$ sources, and that a measurement of the magnetic quadrupole moment (MQM), $\mathcal{M}_d = F_M(0)$, is sensitive to the $\bar{\theta}$ term.

P- and T-conserving (PT) pion interactions are relatively weak, because they proceed through derivatives when originating from the couplings of quarks and gluons, which are chiral-symmetric, or through powers of the small chiral-symmetry breaking parameters, the quark masses $m_{u,d} \sim \bar{m} = \mathcal{O}(m_\pi^2/M_{\rm QCD})$ and the proton charge $e = \sqrt{4\pi\alpha_{em}}$. In the one-nucleon sector the expansion is in powers of $Q/M_{\rm QCD}$, but subtleties in the power counting arise in the two-nucleon (NN) sector [19], where one has to accommodate the large scattering lengths in the ${}^1S_0$ and ${}^3S_1$ waves, and the related presence of the unnaturally shallow bound state in the ${}^3S_1$ wave, the deuteron. Such fine-tuning can be incorporated if the NN LECs are assigned a scaling [20] with inverse powers of the small scale $\gamma \simeq 45$ MeV. Moreover, the strength of pion exchange among nucleons is set by $M_{NN} \sim 4\pi F_\pi^2/m_N \simeq 450$ MeV, and for momenta $Q \lesssim M_{NN}$ pions can be treated perturbatively [20], the deuteron arising when the leading NN contact interaction is summed to all orders. NN observables are amenable to an additional expansion in powers of Q/M_{NN}, although the breakdown scale of this expansion in scattering [20] suggests that M_{NN} is smaller than guessed above by a factor of 2 or 3. This scheme was used to describe the low-energy properties of the deuteron, in particular its PT (charge and magnetic dipole) and $\not{P}T$ (anapole) FFs [21]. We calculate here the $\not{P}\not{T}$ FFs in leading order (LO) for the first time.

At the level of the quark field $q = (u\ d)^T$ and the photon and gluon field strengths $F_{\mu\nu}$ and $G^a_{\mu\nu}$, the lowest-dimension $\not{P}\not{T}$ sources are

$$
\begin{aligned}
\mathcal{L}_{\not{P}\not{T}} &= m_\star\bar{\theta}\,\bar{q}i\gamma_5 q - \frac{i}{2}\bar{q}\left(d_0 + d_3\tau_3\right)\sigma^{\mu\nu}\gamma_5 q\, F_{\mu\nu} \\
&\quad -\frac{i}{2}\bar{q}\left(\tilde{d}_0 + \tilde{d}_3\tau_3\right)\sigma^{\mu\nu}\gamma_5\lambda^a q\, G^a_{\mu\nu} \\
&\quad +\frac{d_W}{6}\epsilon^{\mu\nu\lambda\sigma}f^{abc}G^a_{\mu\rho}G^{b,\rho}_{\nu}G^c_{\lambda\sigma},
\end{aligned}
\tag{3}
$$

in terms of the Pauli isospin matrices $\boldsymbol{\tau}$, the Dirac spin matrices γ_5 and $\sigma^{\mu\nu}$, and the Gell-Mann color matrices λ^a and structure constants f^{abc}. The first term, with $m_\star = m_u m_d/(m_u + m_d) \simeq \bar{m}/2$, incorporates the QCD angle $\bar{\theta}$ [7, 8]. The second (third) term represents the isoscalar d_0 ($\tilde{d}_0$) and isovector d_3 ($\tilde{d}_3$) components of the qEDM (qCEDM). In the last term, d_W is the gCEDM [11]. Because of electroweak $SU(2)\times U(1)$ gauge symmetry, the qEDM and qCEDM are proportional to the vacuum expectation value of the Higgs field, and therefore have effective dimension six [10], being suppressed by two powers of $M_{\not{T}}$. We write [16]

$$
d_i = \mathcal{O}\left(\frac{e\delta\bar{m}}{M_{\not{T}}^2}\right), \tilde{d}_i = \mathcal{O}\left(\frac{4\pi\tilde{\delta}\bar{m}}{M_{\not{T}}^2}\right), d_W = \mathcal{O}\left(\frac{4\pi w}{M_{\not{T}}^2}\right), \tag{4}
$$

where δ, $\tilde{\delta}$, and w are dimensionless parameters that depend on the mechanisms of electroweak and PT breaking, and on the running from the electroweak scale M_W to low energies; their sizes can be calculated in specific high-energy models in terms of coupling constants and complex phases [1, 9]. Our approach is limited to low energies, where the contributions associated with heavier quarks can be buried in the LECs. Effects of higher-dimension $\not{P}\not{T}$ sources should be suppressed by $M_W^2/M_{\not{T}}^2$.

While all interactions in Eq. (3) break P and T, each transforms under $SO(4)$ in a characteristic way [14–17]. The $\bar{\theta}$ term is the fourth component of the same $SO(4)$ vector $P = (\bar{q}\boldsymbol{\tau}q, \bar{q}i\gamma_5 q)$ that leads to isospin breaking [14, 15, 17], and thus generates EFT interactions that transform as $\not{P}\not{T}$ fourth components of $SO(4)$ vectors made out of hadronic fields, with coefficients related to those of PT interactions. Similarly, the qCEDM and qEDM both break chiral symmetry as combinations of fourth and third components of two other $SO(4)$ vectors [16, 17]. The gCEDM does not break chiral symmetry. As in the PT case, we use NDA to estimate the strength of the effective interactions.

The relevant $\not{P}\not{T}$ Lagrangian [14] in terms of the pion field $\boldsymbol{\pi}$ and the heavy-nucleon field $N = (p\ n)^T$ of velocity v^μ and spin S^μ is

$$
\begin{aligned}
\mathcal{L}_{\not{P}\not{T}} &= -\frac{1}{F_\pi}\bar{N}\left(\bar{g}_0\boldsymbol{\pi}\cdot\boldsymbol{\tau} + \bar{g}_1\pi_3\right)N + 2\bar{d}_0\,\bar{N}S^\mu N\,v^\nu F_{\mu\nu} \\
&\quad +\frac{\bar{c}_\pi}{F_\pi}\epsilon^{\mu\nu\alpha\beta}v_\alpha\,\bar{N}S_\beta\boldsymbol{\pi}\cdot\boldsymbol{\tau}N\,F_{\mu\nu} \\
&\quad +\bar{C}_0\left[\bar{N}N\,\partial^\mu\left(\bar{N}S_\mu N\right) - \bar{N}\boldsymbol{\tau}N\cdot\partial^\mu\left(\bar{N}\boldsymbol{\tau}S_\mu N\right)\right] \\
&\quad +\bar{M}\epsilon^{\mu\nu\alpha\beta}v_\alpha\,\bar{N}S_\beta N\,\bar{N}S_\lambda N\,\partial^\lambda F_{\mu\nu} + \ldots,
\end{aligned}
\tag{5}
$$

where $\epsilon^{0123} = 1$,

$$
\bar{g}_0 = \mathcal{O}\left(\bar{\theta}\frac{m_\pi^2}{M_{\rm QCD}}, \tilde{\delta}\frac{m_\pi^2 M_{\rm QCD}}{M_{\not{T}}^2}\right), \bar{g}_1 = \mathcal{O}\left(\tilde{\delta}\frac{m_\pi^2 M_{\rm QCD}}{M_{\not{T}}^2}\right) \tag{6}
$$

are $\not{P}\not{T}$ pion-nucleon couplings,

$$
\bar{d}_0 = \mathcal{O}\left(e\bar{\theta}\frac{m_\pi^2}{M_{\rm QCD}^3}, e\delta\frac{m_\pi^2}{M_{\rm QCD}M_{\not{T}}^2}, ew\frac{M_{\rm QCD}}{M_{\not{T}}^2}\right) \tag{7}
$$

contributes to the short-range isoscalar nucleon EDM,

$$
\bar{c}_\pi = \mathcal{O}\left(e\delta\frac{m_\pi^2}{M_{\rm QCD}M_{\not{T}}^2}\right) \tag{8}
$$

is a $\not{P}\not{T}$ pion-nucleon-photon interaction,

$$
\bar{C}_0 = \mathcal{O}\left(w\frac{4\pi}{m_N\gamma}\frac{M_{\rm QCD}}{M_{\not{T}}^2}\right) \tag{9}
$$

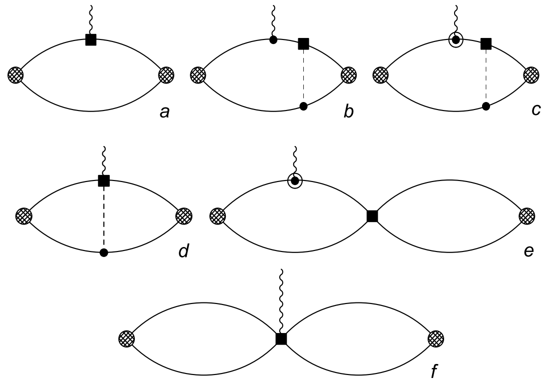

FIG. 1: LO diagrams for the deuteron EDFF (a, b) and MQFF (c, d, e, f). Solid, dashed, and wavy lines represent nucleons, pions, and photons. A square marks $\not{P}\not{T}$, and the other vertices PT interactions: leading (filled circles) and subleading (circled circles). The hatched vertex represents the deuteron state. Only one topology per diagram is shown.

is the leading $\not{P}\not{T}$ NN contact LEC,

$$\bar{M} = \mathcal{O}\left(e\delta \frac{4\pi}{m_N\gamma^2} \frac{m_\pi^2}{M_{NN}M_{\rm QCD}M_{\not{T}}^2}\right) \qquad (10)$$

parametrizes short-distance NN $\not{P}\not{T}$ currents, and "..." stand for terms that only contribute to the FFs at higher orders. For $\bar{\theta}$, the link with isospin violation [14] implies $\bar{g}_0 \simeq \delta m_N(m_d+m_u)\bar{\theta}/2(m_d-m_u) \simeq 2.8\,\bar{\theta}$ MeV, using lattice QCD input [22] for the quark-mass piece of the nucleon mass difference δm_N.

The calculation of the EDFF and MQFF involves at LO the diagrams of Fig. 1, where the squares denote interactions from $\mathcal{L}_{\not{P}\not{T}}$. The circles denote well-known PT interactions, see *e.g.* Ref. [23]. The pion-nucleon vertex is the standard axial-vector coupling, $g_A = 1.27$. The photon vertex denoted by a filled circle is the coupling to the charge e, and that denoted by a circled circle is the magnetic coupling parametrized by the anomalous magnetic moments, the isoscalar $\kappa_0 = -0.12$ and the isovector $\kappa_1 = 3.71$. The hatched circles denote deuteron states [21] obtained from the iteration of the leading NN contact interaction, whose LEC can be eliminated in favor of γ. We use dimensional regularization with power-divergence subtraction [20] at a renormalization scale μ. Our results depend on the ratio $\xi = \gamma/m_\pi$ and on three functions of the momentum in the ratio $x = |\vec{q}|/4\gamma$:

$$F_1(x) = \arctan(x)/x, \qquad (11)$$

which originates in a bubble with one photon coupling and appears also in the charge FF [21], and two complicated functions that result from two-loop diagrams with a pion propagator, which can be expanded as

$$F_2(x) = 1 - x^2\frac{10+65\xi+144\xi^2+72\xi^3}{30(1+\xi)(1+2\xi)^2} + \mathcal{O}(x^4), \quad (12)$$

$$F_3(x) = 1 - x^2\frac{\xi^2(12+8\xi)}{5(1-2\xi)(1+2\xi)^2} + \mathcal{O}(x^4). \qquad (13)$$

The scale of momentum variation is set by 4γ.

The LO deuteron EDFF is due to diagrams a and b,

$$F_D(\vec{q}^{\,2}) = 2\bar{d}_0F_1(x) - \frac{eg_A\bar{g}_1m_N}{6\pi F_\pi^2m_\pi}\frac{1+\xi}{(1+2\xi)^2}F_2(x), \quad (14)$$

where the first term is dominant for $\bar{\theta}$, qEDM, and gCEDM, and the second one for qCEDM. The LO MQFF comes from diagrams c, d, e, and f,

$$\begin{aligned} F_M(\vec{q}^{\,2}) \;=\; & \frac{e(1+\kappa_0)}{2\pi}(\mu-\gamma)\bar{C}_0F_1(x) \\ & +\frac{eg_A}{2\pi F_\pi^2m_\pi}\left[\bar{g}_0(1+\kappa_0)+\frac{\bar{g}_1}{3}(1+\kappa_1)\right] \\ & \times\frac{1+\xi}{(1+2\xi)^2}F_2(x)+\frac{2\gamma}{\pi}(\mu-\gamma)^2\bar{M} \qquad (15)\\ & +\frac{g_A\bar{c}_\pi\gamma}{\pi F_\pi^2}\left(\frac{1-2\xi}{1+2\xi}F_3(x)+2\ln\frac{\mu/m_\pi}{1+2\xi}\right), \end{aligned}$$

where at this order $\bar{g}_0$ originates from $\bar{\theta}$ and qCEDM, $\bar{g}_1$ from qCEDM only, $\bar{C}_0$ from gCEDM, and $\bar{M}$ and $\bar{c}_\pi$ from qEDM.

We can now discuss the implications of the various $\not{P}\not{T}$ sources for the deuteron EDFF and MQFF. In Table I we list the orders of magnitude for the deuteron EDM, d_d, the ratio of deuteron-to-neutron EDMs, d_d/d_n, and the ratio of the deuteron MQM and EDM, $\mathcal{M}_d/d_d$, for the different $\not{P}\not{T}$ sources. Just as for d_n [8, 15, 16], a d_d signal by itself could be attributed to any source with a parameter of appropriate size. For $\bar{\theta}$, qEDM, and gCEDM the deuteron EDFF is determined by the LO isoscalar nucleon EDM, and thus well approximated by the sum of neutron and proton EDM. For $\bar{\theta}$ in particular, using the most important long-range contributions, which appear at NLO, as a lower bound for $\bar{d}_0$ [17, 24], one finds $|d_d| \gtrsim 2.8 \cdot 10^{-4}\,\bar{\theta}\; e\,\text{fm}$. If, however, the dominant $\not{P}\not{T}$ source is the qCEDM, d_d comes mainly from neutral-pion exchange. A measurement of $|d_d|$ significantly larger than $|d_n|$ would be indicative of a qCEDM. A null-measurement at the $10^{-16}\,e\,\text{fm}$ level [6] would strengthen the bounds from the neutron [16] to $\bar{\theta} \lesssim 3\cdot 10^{-13}$ and $\tilde{\delta}, w$, $3\cdot 10^{-2}\delta \lesssim (M_{\not{T}}/3\cdot 10^7\ \text{GeV})^2$. More quantitative statements could be made with lattice-QCD calculations of the EFT LECs.

Additional information comes from the ratio $\mathcal{M}_d/d_d$. For $\bar{\theta}$, $m_d|\mathcal{M}_d|$ is expected to be larger than $|d_d|$, whereas for the dimension-six sources we expect $m_d|\mathcal{M}_d|$ to be of similar size or somewhat smaller than $|d_d|$. For $\bar{\theta}$, $\mathcal{M}_d$ is determined by pion exchange, and we can again use the link with isospin violation [14] to find $\mathcal{M}_d \simeq 2.0\cdot 10^{-3}\,\bar{\theta}\; e\ \text{fm}^2$. An upper bound on $\mathcal{M}_d$ can therefore constrain $\bar{\theta}$ without relying on an estimate of short-range physics via the size of the chiral log, which is necessary when using d_n [8]. Moreover, if $m_d|\mathcal{M}_d|$ is found to be

TABLE I: Orders of magnitude for the deuteron EDM (in units of $e m_d^{-1}$), the ratio of deuteron-to-neutron EDMs, and the ratio of the deuteron MQM and EDM (in units of m_d^{-1}), for $\not P \not T$ sources of effective dimension up to six.

Source	θ	qCEDM	qEDM	gCEDM
$m_d\, d_d/e$	$\bar\theta \frac{m_\pi^2}{M_{\rm QCD}^2}$	$\tilde\delta \frac{m_\pi M_{\rm QCD}^2}{M_{NN} M_{\not T}^2}$	$\delta \frac{m_\pi^2}{M_{\not T}^2}$	$w \frac{M_{\rm QCD}^2}{M_{\not T}^2}$
d_d/d_n	1	$\frac{M_{\rm QCD}^2}{m_\pi M_{NN}}$	1	1
$m_d\, \mathcal{M}_d/d_d$	$\frac{M_{\rm QCD}^2}{m_\pi M_{NN}}$	1	$\frac{\gamma}{M_{NN}}$	1

much smaller than $|d_d|$, the source would likely be qEDM. This shows that a measurement of $\mathcal{M}_d$, in addition to d_n and d_d, would be very valuable, and as a consequence its feasibility is beginning to be investigated [25].

The deuteron EDM and MQM were calculated previously in Ref. [26]. Since these calculations did not use the chiral properties of the fundamental $\not P \not T$ sources, the $\not P \not T$ pion-nucleon interactions were assumed to be all of the same size. When the dominant source is the qCEDM, their results agree with ours. The advantage of our EFT framework is that it has a direct link to QCD by exploiting the chiral properties of the $\not P \not T$ dimension-four and -six operators. This is demonstrated by the $\bar g_2 \bar N \pi_3 \tau_3 N$ interaction used in many previous calculations, which due to its chiral properties only comes in at higher order for all $\not P \not T$ sources [14]. Consequently, for the qCEDM, the ratio of d_d to $\mathcal{M}_d$ depends at LO only on the ratio $\bar g_1/\bar g_0$, which can be measured independently: $\bar g_1$ could be inferred from d_d, and $\bar g_0$ in principle from another observable, such as the proton Schiff moment [16] or the ^{3}He EDM [27]. In addition, the power-counting scheme allows a perturbative framework with analytical results that can be improved systematically. Under the assumption that higher-order results are not afflicted by anomalously-large dimensionless factors, the relative error of our results should be $\gamma/M_{NN} \sim 30\%$, as was explicitly verified for the charge FF [21]. Our estimates for d_d are consistent with those from QCD sum rules [28].

In summary, we have investigated the leading-order, low-energy electric-dipole and magnetic-quadrupole form factors of the deuteron that result from the $\bar\theta$ angle, the quark electric and chromo-electric dipole moments, and the gluon chromo-electric dipole moment. While for qCEDM we expect $|d_d|$ to be larger than $|d_n|$ by a factor $\mathcal{O}(M_{\rm QCD}^2/m_\pi M_{NN})$, for the other $\not P \not T$ sources we have shown that d_d is given by the sum of d_n and d_p. Furthermore, the SM predicts $m_d|\mathcal{M}_d|$ to be larger than $|d_d|$, whereas beyond-the-SM physics prefers $m_d|\mathcal{M}_d|$ smaller than, or of similar size as $|d_d|$. EDM and MQM measurements are therefore complementary.

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