Custodial chiral symmetry in SSH memcircuits

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Custodial symmetries are common in the Standard Model of particle physics. They arise when quantum corrections to a parameter are proportional to the parameter itself. Here, we show that a custodial symmetry of the chiral type is also present in a classical Su-Schrieffer-Heeger (SSH) electrical circuit with memory (memcircuit). In the absence of memory, the SSH circuit supports a symmetry-protected topological edge state. Memory induces nonlinearities that break chiral symmetry explicitly and spreads the state across the circuit. However, the resulting state is still protected against perturbations by the ensuing custodial chiral symmetry. These predictions can be verified experimentally and demonstrate the interplay between symmetry and memory.

A symmetry is said to be custodial if, despite being explicitly broken, it still protects physical quantities (e.g., the mass of particles) from large quantum corrections [1, 2]. Symmetries of this type appear in the Standard Model of particle physics. They arise when quantum corrections to a parameter, as introduced by some symmetry-breaking term in the Lagrangian (e.g., a mass term), are proportional to the parameter itself.

For instance, a custodial SU(2)V symmetry protects the mass relation between the electroweak W and Z gauge bosons from large quantum corrections; or a custodial chiral symmetry protects fermion masses from large radiative corrections.

However, symmetry (like topology) is a concept that extends far beyond quantum systems. As such, it is natural to ask whether custodial symmetries can emerge in classical systems as well. In this Letter, we answer this question in the affirmative. In particular, we use the 1D Su-Schrieffer-Heeger (SSH) model with memory, as realized in electrical circuits with resistive memories [3], as a prototypical example where this type of symmetry can be detected experimentally. The SSH model is a paradigmatic symmetry-protected topological insulator [4, 5], namely it realizes a state of matter with a quantized topological indicator, known as the winding number, associated with a symmetry (chiral in the case of the SSH model) and a finite gap (in the thermodynamic limit).

In fact, there have been intensive studies of electric circuits that may simulate topological systems [6, 7]. The simplest electrical circuit that emulates such a model can be realized with an alternating series of capacitors, $C_1$ and $C_2$, and inductors, $L$ (Fig. 1). The ratio $C_2/C_1$ controls the existence of a symmetry-protected topological mid-gap state at one edge of the circuit. This state can be easily detected as a peak in the impedance as a function of frequency (Fig. 2a), and is localized at the edge of the circuit, as a plot of the voltage drop at the nodes easily shows (Fig. 2b). This state is robust against local perturbations that do not break the chiral symmetry. We would then expect that if we introduced elements in the

circuit that explicitly break such a symmetry, the edge state would easily disappear.

Here, we introduce such elements in the form of resistors with memory (memristive elements) [3] in parallel with the capacitors (Fig. 1b). (The case of memristive elements in series with the capacitors is reported in the Supplementary Material.) Such elements introduce non-Hermiticity and strong nonlinearities, and break chiral symmetry explicitly. In fact, they delocalize the mid-gap state along the whole circuit. However, the resulting state is still robust against perturbations. We will show that the reason for this robustness is the reduction of the original chiral symmetry to a custodial status when memristive elements are added.

SSH circuit – The electric circuit emulators of symmetry-protected topological systems [7] are based on the relation $I = GV$ for idealized linear and memoryless elements. Here, $I$ and $V$ are the profiles of the current.

Figure 1. Schematics of (a) standard and (b) memristive SSH circuit. The numbers in (a) represent the node number. In simulations, we used $C_1 = 0.22 \mu F$ (blue (odd) capacitors), $C_2 = 0.1 \mu F$ (red (even) capacitors), and $L = 10 \mu H$ (all inductors).
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Fig. 1(b) for different values of the low memristance state ν the resistance of standard resistors. (b) Maximum values of the node voltage at the following conductance matrix in the Bloch form:

\[ G = i\omega [d_x(k)\sigma_x + d_y(k)\sigma_y + h_0\mathbf{1}_2]. \] (1)

Here \( d_x(k) = -[C_1 + C_2 \cos(k)], \ d_y(k) = -C_2 \sin(k), \ h_0 = [-\frac{1}{2}\mathbf{1}_2 + C_1 + C_2], \ \mathbf{1}_2 \) is the 2×2 identity matrix, and \( \sigma_{x,y,z} \) are the Pauli matrices. The momentum \( k \) within the first Brillouin zone. An inductor \( L \) connected to the ground has been included in each cell. The conductance matrix \( G \) thus plays the role of the Hamiltonian. In the ideal situation, namely in the absence of memory, dissipation, and/or other chiral symmetry-breaking elements, the eigenvalues of the conductance matrix resemble the energy spectrum of the quantum SSH model [7]. The two energy bands of the quantum model become, in the electrical circuit analogue, two continua of the conductance as a function of the driving frequency \( \omega \).

As mentioned, the mid-gap state may emerge when the lattice has open boundary condition (see Fig. 1). In this case, a localized edge state emerges near the left edge if \( C_2/C_1 < 1 \), and can be detected experimentally by measuring, e.g., the two-point impedance, \( Z_{s0} = (V_s - V_0)/I \), between the source, \( s \), and ground, \( 0 \), nodes of the circuit when the total current \( I \) flows through it. The impedance then exhibits a peak with continua on both sides (Fig 2b). The localized state is associated with the winding number obtained from the equivalent system with periodic boundary condition via the bulk-boundary correspondence [4].

To more clearly see the emergence of the localized edge state, let us write explicitly the conductance matrix for the SSH circuit shown in Fig. 1 with \( N \) unit cells, each containing two capacitors and one inductor. Since the voltage in Fig. 1 is applied to node 1 while node 0 is grounded, the conductance matrix starting from node 1 has the form \( G = A\mathbf{1}_N - i\omega \mathbf{B} \), where \( A = i\omega[-(\omega^2 L)^{-1} + C_1 + C_2] \) contributes to a uniform shift of the spectrum, and

\[ \mathbf{B} = \begin{pmatrix} 0 & C_2 & 0 & \cdots \\ C_2 & 0 & C_1 & \cdots \\ 0 & C_1 & 0 & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}. \] (2)

By defining \( C = -C_2/C_1 \), a voltage profile \( V_{loc} = \)
\((V_1, V_2, \ldots)^T = (1, 0, C, 0, C^2, 0, \ldots)^T\) is an eigenstate of \(G\) at the resonant frequency \(\tilde{\omega} = 1/\sqrt{L(C_1 + C_2)}\). Here the superscript \(T\) denotes the transpose. When \(|C| < 1\), we then clearly see that the voltage profile shows an exponential decay towards the boundary opposite to the voltage source [17]. Therefore, \(V_{inc}\) is a localized state at the left edge of the circuit. This state can be seen in Fig 2 (see also Fig. 3 in the SM) in the configuration when the current is applied only to the first node. In addition, the diagonal part of the above matrix is uniform and can be separated out, indicating that the chiral (sublattice) symmetry is respected. To see this, let us define the following projection operators \(P_1\) and \(P_2\) into the odd and even sites, respectively: \(P_1 = \text{diag}(1, 0, 1, 0, \ldots)\) and \(P_2 = \text{diag}(0, 1, 0, 1, \ldots)\). Then, \((P_1 - P_2)B(P_1 - P_2) = -B\) and the matrix \(B\) respects chiral symmetry.

SSH model with memory – We now show that this picture of band-topology/chiral symmetry changes dramatically in the presence of strong nonlinear effects in the form of, say, memristive elements in parallel with the capacitors (Fig. 1b). To this end, let us employ a widely used model of memristive elements that reproduces the main features of experimentally-realized devices [18]:

\[
R_M = R_{off}(1 - x) + R_{on}x, \quad \text{(3)}
\]

\[
\frac{dx}{dt} = \alpha[\theta(V - V_i)(V - V_i) + \theta(-V - V_i)(V + V_i)]. \quad \text{(4)}
\]

Here \(R_M\) is the memory resistance, \(R_{on}\) and \(R_{off}\) are its limits, \(x \in [0, 1]\) is the internal state variable, \(V_i\) is a positive threshold voltage, and \(\alpha\) is the switching rate. When combined in parallel with the capacitor and driven by \(V = V_0e^{i\omega t}\), we have \(I = [i\omega C + (1/R_M)]V\) for a capacitor-resistor pair. Therefore, we can group the contributions from the resistors by defining \(C_\sigma = C_n + (i\omega R_{M,n})^{-1}\) for \(n = 1, 2\), where \(R_{M,n}\) is the memory resistance of the \(n\)-th memristive elements. This implies that \(I_n = i\omega C_\sigma V_n\). Hence, one may replace \(C_1, C_2\) in Eq. 1 by \(C_\sigma, C_\sigma\).

Due to the memory effect from the memristive elements, a full analysis of the system requires the (numerical) integration over time. However, to extract the main features observed in the simulations, we will use an approximate Fourier analysis. By assuming the form \(I = GV\) still holds for a frequency component, the first thing we notice is that the presence of the memristive elements leads to a complex-valued conductance matrix because the modified circuit dissipates energy. If we write again \(G = d_x\sigma_x + d_y\sigma_y + h_01_2\), we then see that the trajectory \((d_x, d_y)\) now becomes a path in a complex space due to the presence of the memory elements, namely in a 4-dimensional (real) space, not 2-dimensional as before. While a loop in a 2-dimensional plane enclosing the origin cannot be smoothly transformed into a loop that does not enclose the origin, a loop in three or higher dimensions can smoothly deform around the origin without obstruction.

Therefore, the winding number of the original (memoryless) SSH model is no longer faithful in characterizing the topology of the (non-Hermitian) memcircuit. Moreover, nonlinear effects come from the dependence of the memory resistance \(R_M\) on the voltage (Eq. 3). While it is possible to characterize the topology of some non-Hermitian systems by using a biorthogonal basis [19, 20], the presence of nonlinear effects in the memory circuit invalidates the construction of a basis for linear superposition [21]. Therefore, the SSH circuit with memory elements defies the construction of conventional topological quantities.

On the other hand, localized edge states in tight-binding models, known as Shockley-Tamm states [22, 23], may still arise due to symmetry and are not necessarily associated with the band topology. For a 1D lattice with nearest-neighbor interactions and alternating site strengths, the system has a chiral (or sublattice) symmetry. As explained previously, the symmetry can be observed by either constructing the projectors \(P_A, P_B\) in real space or checking if the Bloch Hamiltonian anticommutes with an operator. For the SSH circuit with periodic boundary condition, \(\sigma_z\) anticommutes with the diagonal part of the conduction matrix. Therefore, the chiral symmetry leads to pairs of the eigenstates. For the system shown in Fig. 1, a localized state may emerge with its energy pinned inside the bandgap in order to be consistent with the chiral symmetry. If we had regular resistors \((R_M = R = \text{constant})\) in parallel with the capacitors, we would introduce dissipation, rendering the system non-Hermitian, invalidating the winding number. However, the SSH circuit with regular resistors remains linear, and chiral symmetry still holds after the uniform diagonal part is factored out. Therefore, the edge state is still protected by the chiral symmetry [24], and the impedance shows a broadened peak until the parallel resistance \(R\) is small enough that the current will bypass the capacitors altogether (see Fig. 2h, where the peak decreases dramatically when we reduce \(R\) from \(10^4 \text{ Ohms}\) to 100 Ohms).

Custodial chiral symmetry – If we now introduce memory into the resistors in parallel with the capacitors (Fig. 1b) two additional effects emerge. The nonlinearity introduced by these elements breaks chiral symmetry explicitly: \(\sigma_zB\sigma_z \neq -B\), where \(B\) is the conductance matrix after the uniform diagonal part is removed. The SSH edge state is then no longer an eigenstate of the conduction matrix. Nonetheless, we find the original SSH edge state is still present (as seen in the impedance curve of Fig. 3) but spreads across the circuit (Fig. 2i). However, this effect emerges from the diagonal component of the conductance matrix. To see this, let us add alternating memristive elements \(R_{M,1}\) and \(R_{M,2}\) to the circuit [25]. As discussed before, this leads to the effective capacitors with \(\tilde{C}_i(x_j) = C_i(x_j) + [i\omega R_{M,i}(x_j)]^{-1}\), with
increasing the magnitude of the memristances. Full chiral symmetry, but its violation is suppressed by the presence of memory elements does not respect the operators, \( P \). Here \( A(x_j) = i\omega[-(\omega^2L(x_j)^{-1}+\tilde{C}_L(x_{j-1})+\tilde{C}_R(x_{j+1})], \) where \( \tilde{C}_L \) and \( \tilde{C}_R \) are the capacitor to the left and to the right of the node, and

\[
\mathbf{B} = \begin{pmatrix}
0 & \tilde{C}_2(x_2) & 0 & 0 & \cdots \\
\tilde{C}_2(x_1) & \alpha_1 & \tilde{C}_1(x_3) & 0 & \cdots \\
0 & \tilde{C}_1(x_2) & \alpha_2 & \tilde{C}_2(x_4) & \cdots \\
\vdots & \vdots & \vdots & \vdots & \ddots
\end{pmatrix}.
\] (5)

Here, \( \alpha_j = \tilde{A}(x_{j+1}) - \tilde{A}(x_j) \). The eigenstate of the conductance matrix is now

\[
V_{\text{dis}} = (1, 0, -\frac{\tilde{C}_2(x_1)}{\tilde{C}_1(x_3)}, \alpha_2, -\frac{\tilde{C}_2(x_2)}{\tilde{C}_1(x_3)\tilde{C}_2(x_4)}, \cdots)^T.
\] (6)

spreading over the whole circuit, consistent with the results of Fig. 2. By comparing the matrix \( \mathbf{B} \) above with the matrix \( \mathbf{B} \) of Eq. 7, we see that the nonlinear terms violate the uniform diagonal of the linear case, thus breaking chiral symmetry.

However, note that the chiral-symmetry breaking term is diagonal and depends on \( 1/R_M \). In fact, we can define its strength by taking the diagonals of the matrix Eq. 5. \( \Delta = \text{diag}(0, \alpha_1, \alpha_2, \cdots) \). Using the projection operators, \( P_1 \) and \( P_2 \), we have previously defined, we have \( (P_1 - P_2)\Delta(P_1 - P_2) = \Delta \), so the conductance in the presence of memory elements does not respect the full chiral symmetry, but its violation is suppressed by increasing the magnitude of the memristances \( R_M \).

In field-theory language we would say that the symmetry is broken by a “mass term” and its strength is proportional to the mass itself. This is precisely the definition of custodial symmetry 1. We thus expect that the delocalized state is still protected against perturbations and located in the mid-gap of the continua. This is shown explicitly in Fig. 3 where we randomly perturb the values of the capacitors. Even up to perturbations of 30%, the delocalized state is still clearly visible via the peak in the impedance.

Conclusions – In conclusion, we have shown that the concept of custodial symmetry holds also in the classical case. In particular, we have used a 1D electrical circuit with memristive elements to emulate the SSH model with memory effects. We have shown both analytically and numerically that memory induces nonlinearities that break chiral symmetry explicitly and spreads the in-gap state across the circuit. Nevertheless, the resulting state is still protected against perturbations due to the promotion of the original chiral symmetry to a custodial status. Our predictions, which can be verified experimentally, open up yet another venue to explore some symmetry and topological concepts, that are typically found in quantum systems, in classical settings.

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Author contributions
C.-C.C. and M.D. proposed the theoretical model and
its analysis. Y.V.P. performed all numerical simulations. All authors prepared the manuscript, proofread the paper, made comments, and approved the manuscript.

Competing interests
All authors declare no competing interests.

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Supplemental information: Custodial chiral symmetry in SSH memcircuits

Regular resistors in series with capacitors

If we place regular resistors in series with the capacitors, the chiral-symmetry protected mid-gap state is still visible provided the resistance is not too large so as to close the current flow in the circuit. This is because the resistors in series with the capacitors provide the current at each node of the type \( I = V/[(i\omega C)^{-1} + R] = [i\omega C/(1 + i\omega CR)]V \), with the current going to zero with increasing \( R \). This effect on the mid-gap state is clearly seen in Fig. 4.

Voltage profiles corresponding to Fig. 2

The voltage profiles corresponding to Fig. 2 in the main text is shown in Fig. 5.

Memristive elements in series with capacitors

If the memristive elements are in series with the capacitors, the expression for a single node becomes \( I = V/[(i\omega C)^{-1} + \hat{R}] = [i\omega C/(1 + i\omega CR)]V \). In the resulting SSH memcircuit, the conductance matrix can be obtained by replacing \( C_{1,2} \) in Eq. (1) of the main text by \( \hat{C}_{1,2} = [C_{1,2}/(1+i\omega C_{1,2} R_M,\{1,2\})] \). The conductance matrix then becomes complex-valued and the equations are nonlinear. Therefore, the same arguments as the ones we made in the main text for the memristive elements in parallel with the capacitors hold.

The conduction matrix now becomes \( \mathbf{G} = \hat{A}\mathbf{1}_N + \hat{\mathbf{B}} \). Here \( \hat{A}(x_j) = i\omega[-(\omega^2 L(x_j))^{-1} + \hat{C}_L(x_{j-1}) + \hat{C}_R(x_{j+1})] \), where \( \hat{C}_L \) and \( \hat{C}_R \) are the capacitor to the left and to the right of the node, and

\[
\hat{\mathbf{B}} = \begin{pmatrix}
0 & \hat{C}_2(x_2) & 0 & 0 & \cdots \\
\hat{C}_2(x_1) & \alpha_1 & \hat{C}_1(x_3) & 0 & \cdots \\
0 & \hat{C}_1(x_2) & \alpha_2 & \hat{C}_2(x_4) & \cdots \\
\vdots & \vdots & \vdots & \vdots & \ddots
\end{pmatrix}.
\]  

(7)

Here, the \( \alpha_j = \hat{A}(x_{j+1}) - \hat{A}(x_1) \).

If \( R_{M,\{1,2\}} \gg 1 \), we may replace \( \hat{C}_{1,2} \) by \( i\omega/R_{M,\{1,2\}} \). Then \( \hat{B} \) has the form of the SSH model with alternating off-diagonal elements. The nonlinearity terms on the diagonal, however, still break the symmetry.

The conduction matrix has then the same structure as that with parallel memristive elements. The same arguments then hold regarding the custodial status of the chiral symmetry. The only major difference is that its detection can only be observed at relatively small \( R_M \), namely so long as the current in the circuit is not too small to be detected. In this case, the mid-gap state is weakly delocalized compared to the case of in-parallel memristive elements, as shown in Fig. 6.
Figure 4. SSH circuit simulations with resistors connected in-series with capacitors. (a) Impedance as a function of frequency. (b) Voltage distributions at 89 kHz. (c), (d) Voltage and inverse voltage distributions plots for \( R = 1 \text{ Ohm} \).
Figure 5. Another representation of Fig. 2, $R = 10^4$ Ohms. The boundary state can not be clearly distinguished in (a) as its main feature is the suppression of voltages at even sites (for different frequencies), see (b). However, the boundary state can be distinguished in the inverse voltage plot, (c). (d) Comparison of voltage distributions in the boundary state (red circles) and outside (black squares and blue triangles). This plot indicates the exponential decay in all three cases. The distinguishing feature of the boundary state is that the voltages at even sites are very low.
Figure 6. Boundary state of the SSH memcircuit with in-series connected memristive elements. The boundary state can not be clearly distinguished in (a) as its main feature is the suppression of voltages at even sites. However, the boundary state can be distinguished in the inverse voltage plot, (b). The parameters used in this simulation are $R_{on} = 1$ Ohm, $R_{off} = 10$ Ohm, $V_t = 0.1$ V, $R(t = 0) = 1$ Ohm. (c) Impedance as a function of frequency. (d) Voltage distributions at various frequencies.