Three Steps to Chaos—Part II: A Chua’s Circuit Primer

Michael Peter Kennedy

Abstract—Linear system theory provides an inadequate characterization of sustained oscillation in nature. In this two-part exposition of oscillation in piecewise-linear dynamical systems, we guide the reader from linear concepts and simple harmonic motion to nonlinear concepts and chaos. By means of three worked examples, we bridge the gap from the familiar parallel RLC network to exotic nonlinear dynamical phenomena in Chua’s circuit. Our goal is to stimulate the reader to think deeply about the fundamental nature of oscillation and to develop intuition into the chaos-producing mechanisms of nonlinear dynamics. In order to exhibit chaos, an autonomous circuit consisting of resistors, capacitors, and inductors must contain (1) at least one nonlinear element, (2) at least one locally active resistor, and (3) at least three energy-storage elements. Chua’s circuit is the simplest electronic circuit that satisfies these criteria. In addition, this remarkable circuit is the only physical system for which the presence of chaos has been proved mathematically. The circuit is readily constructed at low cost using standard electronic components and exhibits a rich variety of bifurcations and chaos. In Part I of this two-part paper, we plot the evolution of our understanding of oscillation from linear concepts and the parallel RLC resonant circuit to piecewise-linear circuits and Chua’s circuit. We illustrate by theory, simulation, and laboratory experiments the concepts of equilibria, stability, local and global behavior, bifurcations, and steady-state solutions. In Part II, we study bifurcations and chaos in a robust practical implementation of Chua’s circuit.

I. INTRODUCTION

Chaos is characterized by a stretching and folding mechanism; nearby trajectories of a dynamical system are repeatedly pulled apart exponentially and folded back together. In Part I of this tutorial paper, we saw that the steady-state solution of a second-order circuit can be either a DC equilibrium point or a limit cycle; chaos is not possible. Nevertheless, our observations of some simple two-dimensional circuits suggest how one might create the required stretching and folding mechanism. We noted how two adjacent trajectories are separated exponentially along an eigenplane by a pair of unstable complex eigenvalues. This mechanism can be exploited to provide stretching; folding may be accomplished with a third dimension and a nonlinearity.

Consider a third-order autonomous circuit described by

\[ \dot{X} = F(X), \quad X(0) = X_0. \tag{1} \]

Shilnikov’s theorem [1], [2], states that if an equilibrium point \( X_Q \) of this circuit has a pair of unstable complex conjugates

\[ \sigma \pm j\omega \] (\( \sigma < 0, \omega \neq 0 \)) and an unstable real eigenvalue \( \gamma \) where \( |\sigma| < |\gamma| \), and the vector field \( F(X) \) has a homoclinic orbit through \( X_Q \), then there is a perturbation \( F' \) of \( F \) (which may be obtained by changing one or more parameters of the system) such that \( F' \) has transversal homoclinic orbits and horseshoes. The presence of transversal homoclinic orbits implies the existence of infinitely many unstable periodic orbits of arbitrarily long period as well as complicated bounded nonperiodic solutions of (1) called chaotic trajectories.

Although we have stated it for the case \( \sigma < 0, \gamma > 0 \), Shilnikov’s theorem also applies when the equilibrium point has an unstable pair of complex conjugate eigenvalues and a stable real eigenvalue. In that case, it is somewhat easier to visualize the stretching and folding of trajectories close to a homoclinic orbit.

Consider the trajectory of a three-region piecewise-linear vector field shown in Fig. 1. We assume that the equilibrium point \( P_- \) has a stable real eigenvalue \( \gamma_1 \) (whose eigenvector is \( E'(P_-) \)) and an unstable complex conjugate pair of eigenvalues \( \sigma_1 \pm j\omega_1 \), the real and imaginary parts of

\[ \sigma_1 \pm j\omega_1 \] (where \( \sigma_1 < 0, \omega_1 \neq 0 \)). This equation \( \sigma_1 \) and \( \omega_1 \) are the real and imaginary parts of the pole of the system in the complex plane. The pole is a root of the characteristic equation of the system, and it determines the system’s stability. If the pole lies in the left half of the complex plane, the system is stable; if it lies in the right half, the system is unstable.

![Fig. 1. Stretching and folding mechanism of chaos generation close to a homoclinic orbit in a three-region piecewise-linear vector field. A trajectory spirals away from \( P_- \) along the eigenplane \( E'(P_-) \) until it enters the \( D_0 \) region, where it is folded back into \( D_{-1} \) and returns to the unstable eigenplane \( E'(P_-) \) close to \( P_- \).](image)

1A homoclinic orbit is the union of an equilibrium point \( E \) and a trajectory \( T \) that approaches \( E \) as \( t \to \infty \) and as \( t \to -\infty \) [1], [3]. Clearly, \( E \) is stable in the direction along which \( T \) approaches \( E \) as \( t \to -\infty \) and unstable in the direction along which \( T \) approaches \( E \) as \( t \to \infty \); an equilibrium point that is stable in one direction and unstable in another is called a saddle.

2The details of transversal homoclinic orbits and horseshoes are beyond the scope of this paper; we refer the reader to [1] for a rigorous treatment of these topics.

3Well-behaved periodic motion with any desired period can be obtained from a chaotic system by stabilizing an unstable periodic orbit of the desired length [4].
whose eigenvectors span the plane \( E'(P_-) \) [5], as shown. A trajectory originating from a point \( \mathbf{x}_0 \) on \( E'(P_-) \) spirals away from the equilibrium point along \( E'(P_-) \) until it enters the \( D_0 \) region, where it is folded back into \( D_{-1} \). Upon reentering \( D_{-1} \), the trajectory is pulled toward \( P_- \) roughly in the direction of the real eigenvector \( E'(P_-) \), as shown.

Now imagine what would happen if the trajectory entering \( D_{-1} \) from \( D_0 \) were in precisely the direction \( E'(P_-) \). Such a trajectory would follow \( E'(P_-) \) toward \( P_- \), reaching the equilibrium point asymptotically as \( t \to \infty \). Similarly, if we were to follow this trajectory backward in time though \( D_0 \) and back onto \( E'(P_-) \) in \( D_{-1} \), it would then spiral toward \( P_- \), reaching it asymptotically as \( t \to -\infty \). The trajectory thus formed would be a homoclinic orbit, reaching the same equilibrium point \( P_- \) asymptotically in forward and reverse time.

While the homoclinic orbit itself is not structurally stable, and therefore cannot be observed experimentally, it is indicative of complicated dynamical behavior nearby [1]. In this example, we see that a trajectory lying close to the postulated homoclinic orbit exhibits similar qualitative behavior: it spirals away from \( P_- \) along the unstable real eigenvector \( E'(P_-) \), is folded in \( D_0 \), reenters \( D_{-1} \) above \( E'(P_-) \), and is pulled back toward \( E'(P_-) \) only to be spun away from \( P_- \) once more. Thus, two trajectories starting from distinct initial states close to \( P_- \) on \( E'(P_-) \) are stretched apart exponentially along the unstable eigenplane before being folded in \( D_1 \) and reinjected close to \( P_- \). This recurrent stretching and folding continues \( \infty \), producing a chaotic steady-state solution.

The Genesis of Chua’s Circuit

While on a visit to Japan in 1983, having witnessed a futile attempt at producing chaos in an electrical analog of Lorenz’s equations, Leon Chua was prompted to develop a chaotic electronic circuit. He realized that chaos could be produced in a piecewise-linear circuit if it possessed at least two unstable equilibrium points—one to provide stretching, and the other to fold trajectories. With this insight, he systematically identified those third-order piecewise-linear circuits containing a single voltage-controlled nonlinear resistor that could produce chaos. Specifying that the driving-point (DP) characteristic of the voltage-controlled nonlinear resistor \( N_R \) should be chosen to yield at least two unstable equilibrium points, he invented the circuit shown in Fig. 2.

Let the nonlinear resistor \( N_R \) in Chua’s circuit have a piecewise-linear DP characteristic as shown in Fig. 3. Imagine that the values of the parameters are chosen such that the circuit possesses three equilibrium points (one at the origin with locally negative slope or conductance \( G_a \), and two in the outer regions with locally negative conductance \( G_b \)) and that all three equilibrium points are unstable. Associated with each equilibrium point are three eigenvalues. We assume that the equilibrium point at the origin has an unstable real eigenvalue and a stable pair of complex conjugate eigenvalues; we saw in Section VI of Part I that this is possible. In addition, suppose that the outer equilibrium point \( P_- \) has a stable real eigenvalue and an unstable complex pair. Two trajectories starting close together on the eigenplane in the outer region would be stretched apart as they spiralled away from the equilibrium point. If they could be folded back by the dynamics in the inner region and reinjected toward \( P_- \) along the stable real eigenvector, a homoclinic orbit would be produced, and chaos would result.

Soon after its conception, the rich dynamical behavior of Chua’s circuit was confirmed by computer simulation [6] and experiment [7]. Since then, there has been an intensive effort to understand every aspect of the dynamics of this circuit with a view to developing it as a paradigm for learning, understanding, and teaching about nonlinear dynamics and chaos.

That the circuit does in fact exhibit chaos in the sense of Shilnikov was proved by Chua et al. in 1986 [2]. More recently, by adding a linear resistor in series with the inductor, the circuit has been generalized to the canonical Chua’s oscillator [8]. This circuit is canonical in the sense that every continuous three-dimensional odd-symmetric piecewise-linear vector field may be mapped onto the circuit. The circuit can thus exhibit every dynamical behavior known to be possible in a system described by a continuous odd-symmetric three-region piecewise-linear vector field. With the appropriate choice of parameters, the circuit can be made to follow the classic period-doubling, intermittency, and torus breakdown routes to chaos. For a comprehensive bibliography of papers on Chua’s circuit, we refer the reader to Chua’s historical review paper [9].

II. CHUA’S CIRCUIT

In Part I of this two-part paper, we plotted (with hindsight) the evolution of Chua’s circuit from the classic parallel RLC resonant circuit. From periodic motion and two-dimensional dynamics, we learned about piecewise-linear analysis and three-dimensional dynamics. In Part II, we study in detail the geometry and state-space dynamics of Chua’s circuit. We concentrate on a particular set of parameters and behaviors which are readily reproducible by simulation and experiment.
In order to produce at least two unstable equilibrium points without sacrificing the benefits of piecewise-linear analysis, we specify a piecewise-linear DP characteristic for the nonlinear resistor $N_R$, as shown in Fig. 3. This characteristic is defined analytically as follows:

$$ I_R = \begin{cases} G_a V_R + (G_b - G_a) E & \text{if } V_R < -E \\ G_d V_R & \text{if } -E \leq V_R \leq E \\ G_b V_R + (G_a - G_b) E & \text{if } V_R > E \end{cases} $$

where $E > 0$, $G_a < 0$, and $G_b < 0$. In contrast with the nonlinear resistor considered in Part I, note that $G_a$ and $G_b$ are now both negative.

**Piecewise-Linear Description of Chua's Circuit**

We have seen that this circuit may be described by three ordinary differential equations (state equations). Choosing $I_3, V_2$ and $V_1$ as state variables, we write the equations shown in (2), (3), and (4) at the bottom of this page, where $G = 1/R$, $G_a = G + G_2$, and $G_b = G + G_3$.

Because of the piecewise-linear nature of $N_R$, the vector field of Chua's circuit may be decomposed into three distinct affine regions: $V_1 < -E$, $|V_1| \leq E$, and $V_1 > E$. We call these the $D_{-1}$, $D_0$, and $D_1$ regions, respectively. Using piecewise-linear analysis, we examine each region separately, and then glue the pieces together. First, we review some results concerning linear algebra and ordinary differential equations.

**Eigenvalues and Eigenvectors Revisited**

Consider the three-dimensional autonomous affine dynamical system

$$ \dot{X}(t) = AX(t) + b, X(0) = X_0, $$

where $A$ is the (constant) system matrix and $b$ is a constant vector. $X(t)$ is a trajectory originating from the initial state $X_0$. We saw in Part I that the equilibrium point $X_Q$ of this system is defined by

$$ X_Q = -A^{-1}b, $$

if $A^{-1}$ exists, and that the dynamics close to $X_Q$ are governed locally by the linear system

$$ \dot{x}(t) = Jx(t) $$

where $J$ is simply the system matrix $A$ in the case of a linear or affine system.

If the eigenvalues $\lambda_1, \lambda_2$, and $\lambda_3$ of $J$ are distinct, then every solution $x(t)$ of (6) may be expressed in the form

$$ x(t) = c_1 \exp(\lambda_1 t) \xi_1 + c_2 \exp(\lambda_2 t) \xi_2 + c_3 \exp(\lambda_3 t) \xi_3, $$

where $\xi_1, \xi_2$, and $\xi_3$ are the (possibly complex) eigenvectors associated with the eigenvalues $\lambda_1, \lambda_2$, and $\lambda_3$, respectively, and the $c_k$'s are (possibly complex) constants that depend on the initial state $X_0$ [10].

In the special case when $J$ has one real eigenvalue $\gamma$ and a complex conjugate pair of eigenvalues $\sigma \pm j\omega$, the solution of (6) has the form:

$$ x(t) = C_1 \exp(\gamma t) \xi_1 + 2C_2 \exp(\sigma t) \{ \cos(\omega t + \phi) \eta_1 - \sin(\omega t + \phi) \eta_2 \} $$

where $\eta_1$ and $\eta_2$ are the real and imaginary parts of the eigenvectors associated with the complex conjugate pair of eigenvalues, $\xi_1$ is the eigenvector defined by $J \xi_1 = \gamma \xi_1$, and $c_1, c_2, and \phi_1$ are real constants that are determined by the initial conditions.

Let us relabel the real eigenvalue $E^r$ and define $E^c$ as the complex eigenplane spanned by $\eta_1$ and $\eta_2$.

We can think of the solution $x(t)$ of (6) as being the sum of two distinct components $x_r(t) \in E^r$ and $x_c(t) \in E^c$:

$$ x_r(t) = c_1 \exp(\gamma t) \xi_1, $$

$$ x_c(t) = 2c_2 \exp(\sigma t) \{ \cos(\omega t + \phi) \eta_1 - \sin(\omega t + \phi) \eta_2 \}. $$

Because the Jacobian matrix of an affine system is simply the system matrix $A$, the complete solution $X(t)$ of (5) may be found by translating the origin of the linearized coordinate system to the equilibrium point $X_Q$. Thus,

$$ X(t) = X_Q + x(t) $$

$$ = X_Q + x_r(t) + x_c(t). $$

We can determine the qualitative behavior of the complete solution $X(t)$ by considering separately the components $x_r(t)$ and $x_c(t)$ along $E^r$ and $E^c$, respectively.

If $\gamma > 0$, $x_r(t)$ grows exponentially in the direction of $E^r$; if $\gamma < 0$, $x_r(t)$ tends asymptotically to zero. When $\gamma > 0$ and $\omega \neq 0$, $x_c(t)$ spirals away from $X_Q$ along the complex eigenplane $E^c$, and if $\sigma < 0$, $x_c(t)$ spirals toward $X_Q$ along $E^c$. 

$$ \frac{dI_1}{dt} = -\frac{1}{L} V_2 $$

$$ \frac{dV_2}{dt} = \frac{1}{C_2} I_3 - \frac{G}{C_2} (V_2 - V_1) $$

$$ \frac{dV_1}{dt} = \frac{G}{C_2} (V_2 - V_1) - \frac{1}{C_1} f(V_1) = \begin{cases} \frac{G}{C_1} V_2 - \frac{G}{C_2} V_1 - \left( \frac{G_a - G_b}{C_1} \right) E & \text{if } V_1 < -E \\ \frac{G}{C_1} V_2 - \frac{G}{C_2} V_1 & \text{if } -E \leq V_1 \leq E \\ \frac{G}{C_1} V_2 - \frac{G}{C_2} V_1 - \left( \frac{G_a - G_b}{C_1} \right) E & \text{if } V_1 > E \end{cases} $$
We remark that the vector $E'$ and plane $E''$ are invariant under the flow (5). If $X(0) \in E'$, then $X(t) \in E'$ for all $t$; if $X(0) \in E''$, then $X(t) \in E''$ for all $t$. An important consequence of this is that a trajectory $X(t)$ cannot cross through the complex eigenspace $E''$. Suppose $X(t_0) \in E''$ at some time $t_0$; then $X(t) \in E''$ for all $t > t_0$.

A state $X \in \mathbb{R}^3$ lies on the plane $E''$ if $(X - X_Q) \cdot n = 0$, where $\cdot$ denotes the dot product and $n$ is the normal vector, which is perpendicular to $E''$. Thus, the plane $E''$ through an equilibrium point $X_Q$ is characterized by the normal vector $n$.

We are now ready to examine the dynamics of Chua’s circuit in each region. We look at $D_0$ first.

**The Middle Region** ($|V_1| \leq E$)

When $|V_1| \leq E$, Chua’s circuit is described by

$$\begin{align*}
dI_3 &= -\frac{1}{L} V_2 \\
dV_2 &= \frac{1}{C_2} I_3 - \frac{G}{C_2} (V_2 - V_1) \\
dV_1 &= \frac{G}{C_1} V_2 - \frac{G_0}{C_1} V_1
\end{align*}$$

The $D_0$ equivalent circuit is simply the linear parallel RLC circuit shown in Fig. 4.

This linear circuit has a single equilibrium point at the origin whose stability is completely specified by the eigenvalues of $J_{F_a}$

$$J_{F_a} = \begin{bmatrix} 0 & -\frac{1}{G} & 0 \\ -\frac{G}{C_2} & 0 & -\frac{G_0}{C_1} \\ 0 & \frac{G}{C_1} & -\frac{G_0}{C_1} \end{bmatrix}$$

namely, the zeros of the characteristic polynomial

$$\lambda^3 + \left(\frac{G}{C_2} + \frac{G_0}{C_1}\right) \lambda^2 + \left(\frac{1}{LC_2} + \frac{GG_0}{C_1C_2}\right) \lambda + \frac{G_0}{LC_1C_2} = 0$$

Throughout this paper, we consider a fixed set of component values: $L = 18 \text{ mH}$, $C_2 = 100 \text{ nF}$, $C_1 = 10 \text{ nF}$, $G_a = -55/60 \text{ mS} = -757.576 \mu\text{S}$, $G_b = -9/22 \text{ mS} = -409.091 \mu\text{S}$, and $E = 1 \text{ V}$.

When $G = 550 \mu\text{S}$, the eigenvalues of $J_{F_a}$ are:

$\gamma_0 \approx 25291$

$\sigma_0 \pm j\omega_0 \approx -5842 \pm j19720$

Associated with the unstable real eigenvalue $\gamma_0$ in the $D_0$ region is an eigenvector $E''(0)$ that is defined by

$$J_{F_a} E''(0) = \gamma_0 E''(0)$$

Writing $E''(0) = [x, y, z]^T$, we have

$$\begin{bmatrix} \gamma_0 & \frac{1}{G} & 0 \\ -\frac{G}{C_2} & \gamma_0 + \frac{G_0}{C_1} & -\frac{G_0}{C_1} \\ 0 & \frac{G}{C_1} & \gamma_0 + \frac{G_0}{C_1} \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

Normalized to $z = 1$, the corresponding eigenvector is:

$$E''(0) = \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} \gamma_0 + \frac{G_0}{C_1} \\ \frac{G}{C_1} \left(\gamma_0 + \frac{G_0}{C_1}\right) + \frac{G_0}{C_1} \end{bmatrix}$$

The real and imaginary parts of the complex eigenvectors associated with $\sigma_0 \pm j\omega_0$ span a complex eigenplane, which we denote by $E''(0)$. The vector normal to $E''(0)$ is

$$\begin{bmatrix} -\frac{G}{C_2} \left(\gamma_0 + \frac{G_0}{C_1}\right) + \frac{G_0}{C_1} \\ \frac{G}{C_1} \left(\gamma_0 + \frac{G_0}{C_1}\right) + \frac{G_0}{C_1} \end{bmatrix}$$

where $\gamma_0$ is the real eigenvalue in $D_0$.

This plane is characterized by the fact that for every $X \in E''(0)$, $J_{F_a} X \in E''(0)$. Thus, a trajectory starting on the eigenplane $E''(0)$ evolves along $E''(0)$. We remarked earlier that a trajectory cannot cross through an eigenplane. An important consequence of this is that a trajectory that originates from an initial state above the eigenplane remains indefinitely above the plane, and one that originates below $E''(0)$ remains forever below the plane.

**Qualitative Description of the $D_0$ Dynamics**: A trajectory starting from some initial state $X_0$ in the $D_0$ region may be decomposed into its components along the complex eigenplane $E''(0)$ and along the eigenvector $E'(0)$. When $\gamma_0 > 0$ and $\sigma_0 < 0$, the component along $E'(0)$ grows exponentially. Adding the two components, we see that a trajectory starting slightly above the stable complex eigenplane $E''(0)$ spirals toward the origin along this plane while the component in the direction $E''(0)$ grows exponentially. Adding the two components, we see that a trajectory starting slightly above the stable complex eigenplane $E''(0)$ shrinks in magnitude, the unstable component grows exponentially, and the trajectory follows a helix of exponentially decreasing radius whose axis lies in the direction of $E''(0)$; this is illustrated in Fig. 5.
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Fig. 6. Equivalent circuit of Fig. 2 in the D1 region, \( R_b = 1/G_b \), 
\( I' = (G_b - G_a)E \) when \( V_1 < -E \) and \( I' = (G_a - C_a)E \) when \( V_1 > E \).

The Outer Regions (\(|V_1| > E\))

In the outer regions, Chua's circuit (with a piecewise-linear \( N_R \)) is described by

\[
\frac{dI_2}{dt} = \frac{1}{L} V_2 \\
\frac{dV_2}{dt} = \frac{1}{C_2} I_3 - \frac{G}{C_2} (V_2 - V_1) \\
\frac{dV_1}{dt} = \frac{G}{C_1} V_2 - \frac{G}{C_1} V_1 - \frac{I'}{C_1}
\]

(7)

where \( I' = (G_b - G_a)E \) when \( V_1 < -E \) (the D_1 region) and \( I' = (G_b - G_a)E \) when \( V_1 > E \) (the D_1 region). The \( D_1 \) and \( D_1 \) affine equivalent circuits consist of a linear parallel RLC circuit with resistance \( R_b = 1/G_b \) and a shunt DC current source \( I' \), as shown in Fig. 6.

The equilibrium points \( P_- \) and \( P_+ \) of the outer regions are given by \( V_2 = 0, V_1 = -I'/G_b \), and \( I_3 = -G V_1 = I'G/G_b \). Note that an equilibrium point is simply a DC solution of the equivalent circuit and may be determined by short-circuiting \( L \) and open-circuiting \( C_1 \) and \( C_2 \) [5]. The equilibrium points of the outer regions are thus

\[
P_- = \begin{bmatrix} G (G_a - G_b)E \\ G + G_b \end{bmatrix}, \quad P_+ = \begin{bmatrix} G (G_a - G_b)E \\ G + G_a \end{bmatrix}
\]

If the equilibrium point \( P_- \) lies outside the \( D_1 \) region, then it is called a virtual equilibrium point [5]. While this is a valid solution of the affine \( D_1 \) equivalent circuit described by (7), it is not an equilibrium point of the circuit itself. For example, the equilibrium point \( P_+ \) lies outside \( D_1 \) (and so is a virtual equilibrium point) if

\[
\frac{G (G_a - G_b)E}{G + G_a} > -E
\]

Equivalently, the point \( P_+ \) is an equilibrium point of Fig. 2 (when \( G > 0 \)) only if \(-G_a < G < -G_b\).

We can determine the stability of the equilibrium points and the dynamics of the outer regions by examining the Jacobian matrix

\[
J_{FB} = \begin{bmatrix} 0 & \frac{1}{C_2} & 0 \\ \frac{1}{G} & \frac{G}{C_2} & \frac{G}{C_1} \\ 0 & \frac{G}{C_1} & \frac{G}{C_1}
\end{bmatrix}
\]

whose eigenvalues are the zeroes of the characteristic polynomial

\[
\lambda^3 + \left( \frac{G}{C_2} + \frac{G}{C_1} \right) \lambda^2 + \left( \frac{1}{LC_2} + \frac{G G_a}{C_2 C_1} \right) \lambda + \frac{G}{C_1}
\]

\[
= \frac{LC_1 C_2}{G}
\]

The \( D_1 \), \( D_1 \), and \( D_1 \) equivalent circuits are not small-signal (local) equivalent circuits; they model the large-signal (global) behavior of the system in the outer regions.

With all other component values as before, and \( G = 550 \mu S \), the eigenvalues of \( J_{FB} \) are:

\[
\gamma_1 \approx -23284 \\
\sigma_1 \pm j \omega_1 \approx 1022 \pm j 1920
\]

Associated with the stable real eigenvalue \( \gamma_1 \) in the \( D_1 \) region is an eigenvector \( E'(P_+) \), which is defined by

\[
J_{FB} E'(P_+) = \gamma_1 E'(P_+).
\]

Writing \( E'(P_+) = [x, y, z]^T \), we have

\[
\begin{bmatrix} \gamma_1 & \frac{1}{C_2} & 0 \\ \frac{1}{G} & \gamma_1 + \frac{G}{C_1} & -\frac{G}{C_1} \\ 0 & -\frac{G}{C_1} & \gamma_1 + \frac{G}{C_1}
\end{bmatrix} \begin{bmatrix} x \\ y \\ z
\end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0
\end{bmatrix}
\]

Normalized to \( z = 1 \), the real eigenvector is:

\[
E'(P_+) = \begin{bmatrix} x \\ y \\ z
\end{bmatrix} = \begin{bmatrix} (\gamma_1 + \frac{G}{C_1}) (\gamma_1 + \frac{G}{C_1}) \frac{G}{C_1} \\ \frac{G}{C_1} \gamma_1 + \frac{G}{C_1} \\ 1
\end{bmatrix}
\]

The real and imaginary parts of the complex eigenvectors associated with \( \sigma_1 \pm j \omega_1 \) span a complex eigenplane, which we denote \( E''(P_+) \). The vector normal to \( E''(P_+) \) is

\[
\begin{bmatrix} -\frac{L C_1}{G} (\gamma_1 + \frac{G}{C_1}) (\gamma_1 + \frac{G}{C_1}) \frac{G}{C_1} - \frac{G}{C_1} \\ \frac{C_1}{G} \gamma_1 + \frac{G}{C_1} \\ 1
\end{bmatrix}
\]

where \( \gamma_1 \) is the real eigenvector in \( D_1 \).

This eigenvector is characterized by the fact that for every \( X \in E''(P_+) \), \( J_{FB} X \in E''(P_+) \) so a trajectory starting on \( E''(P_+) \) evolves along \( E''(P_+) \). Once again, we note that a trajectory that originates from an initial state above the complex eigenplane remains indefinitely above the plane, and one that originates below remains below.

**Qualitative Description of the Dynamics for \(|V_1| > E|**

Associated with the stable real eigenvalue \( \gamma_1 \) in the \( D_1 \) region is the eigenvector \( E'(P_+) \). The real and imaginary parts of the complex eigenvectors associated with \( \sigma_1 \pm j \omega_1 \) define a complex eigenplane \( E''(P_+) \).

A trajectory starting from some initial state \( X_0 \) in the \( D_1 \) region may be decomposed into its components along the complex eigenplane \( E''(P_+) \) and the eigenvector \( E'(P_+) \). When \( \gamma_1 < 0 \) and \( \sigma_1 > 0 \), the component on \( E'(P_+) \) spirals away from \( P_+ \) along this plane while the component in the direction of \( E'(P_+) \) tends asymptotically toward \( P_+ \). Adding the two components, we see that a trajectory starting close to the stable real eigenvector \( E'(P_+) \) above the complex eigenplane moves toward \( E''(P_+) \) along a helix of exponentially increasing radius. Since the component along \( E'(P_+) \) shrinks exponentially in magnitude and the component on \( E''(P_+) \) grows exponentially, the trajectory is quickly flattened onto \( E''(P_+) \), where it spirals away from \( P_+ \) along the complex eigenplane; this is illustrated in Fig. 7.

Note that because of the strong rate of contraction along the \( E''(P_+) \) direction, a trajectory spends most of its time in \( D_1 \) coexisting very close to \( E''(P_+) \). Consequently, the system appears locally to be two-dimensional and can therefore be
readily analyzed by using one-dimensional discrete maps (see, e.g., [11]).

By symmetry, the equilibrium point \( P_- \) in the \( D_- \) region has three eigenvalues: \( \gamma_1 \) and \( \sigma_1 \pm j \omega_1 \). The eigenvector \( E''(P_-) \) is associated with the stable real eigenvalue \( \gamma_1 \); the real and imaginary parts of the eigenvectors associated with the unstable complex pair \( \sigma_1 \pm j \omega_1 \) define an eigenplane \( E''(P_-) \) along which trajectories spiral away from \( P_- \).

**Global Behavior**

The global dynamics of Chua’s circuit may be determined by piecing together the three-dimensional vector fields of the three regions \( D_- \), \( D_0 \), and \( D_1 \).

The equilibrium points of the entire circuit are defined by

\[
\begin{align*}
0 &= -\frac{1}{L}V_2 \\
0 &= \frac{1}{C_2}I_R - \frac{G}{C_2}(V_2 - V_1) \\
0 &= \frac{G}{C_1}(V_2 - V_1) - \frac{1}{C_1}I_R
\end{align*}
\]

Equivalently, one open-circuits the capacitors \( C_1 \) and \( C_2 \), and short-circuits the inductor \( L \) to find the dc solutions. This is illustrated in Fig. 8. Clearly, the dc solution of this circuit is \( I_R = -GV_R \). The equilibrium points may be determined graphically by intersecting the load line \( I_R = -GV_R \) with the DP characteristic \( I_R = f(V_R) \) of the nonlinear resistor \( N_R \), as shown in Fig. 9 [5]. When \( G > |G_a| \) or \( G < |G_a| \), the circuit has a unique equilibrium point at the origin (and two virtual equilibria \( P_- \) and \( P_+ \)); otherwise, it has three equilibrium points at \( P_- \), 0, and \( P_+ \).

In the following discussion, we consider the global behavior of the circuit using our chosen set of parameters with \( R \) in the range \( 0 \leq R \leq 2000 \Omega \) (500 \( \mu \)S \( \leq G < \infty \) S).

Fig. 10 is a series of simulations of the circuit shown in Fig. 20 with the following parameter values: \( L = 18 \) mH, \( C_2 = 100 \) nF, \( C_1 = 10 \) nF, \( G_a = -55/60 \) mS = \(-757.576\) \( \mu \)S, \( G_b = -9/22 \) mS = \(-409.091\) \( \mu \)S, and \( E = 1 \) V. \( R_0 = 12.5 \Omega \) models the parasitic series resistance of a real inductor. \( R \) is our bifurcation parameter.

**Equilibrium Point and Hopf Bifurcation:** When \( R \) is large (2000 \( \Omega \)), the outer equilibrium points \( P_- \) and \( P_+ \) are stable (\( \gamma_1 < 0 \) and \( \sigma_1 < 0, \omega_1 \neq 0 \)); the inner equilibrium point 0 is unstable (\( \gamma_0 > 0 \) and \( \sigma_0 < 0, \omega_0 \neq 0 \)).

Depending on the initial state of the circuit, the system remains at one outer equilibrium point or the other. Let us assume that we start at \( P_+ \) in the \( D_1 \) region. This equilibrium point has one negative real eigenvalue and a complex pair with negative real parts. The action of the negative real eigenvalue \( \gamma_1 \) is to squeeze trajectories down onto the complex eigenplane \( E''(P_+) \), where they spiral toward the equilibrium point \( P_+ \).

Fig. 10(a) shows the geometry of the piecewise-linear vector space when \( R = 2000 \Omega \) and a trajectory \( X(t) \) that spirals toward the steady-state equilibrium point solution \( P_+ \).

As the resistance \( R \) is decreased, the real part of the complex pair of eigenvalues changes sign and becomes positive. Correspondingly, the outer equilibrium points become unstable as \( \sigma_1 \) passes through 0; this is called a Hopf bifurcation. The real eigenvalue of \( P_+ \) remains negative, so trajectories in the \( D_1 \) region converge toward the complex eigenplane \( E''(P_+) \). However, they spiral away from the equilibrium point \( P_+ \) along \( E''(P_+) \) until they reach the dividing plane \( U_1 \) (defined by \( V_1 \equiv E \)) and enter the \( D_0 \) region.

The equilibrium point at the origin in the \( D_0 \) region has a stable complex pair of eigenvalues and an unstable real
eigenvalue. Trajectories that enter the $D_0$ region on the complex eigenplane $E'(0)$ are attracted to the origin along this plane. Trajectories that enter $D_0$ from $D_1$ below or above the eigenplane either cross over to $D_{-1}$ or are turned back toward $D_1$, respectively. For $R$ sufficiently large, trajectories that spiral away from $P_+$ along $E'(P_+)$ and enter $D_0$ above $E'(0)$ are returned to $D_1$, producing a stable period 1 limit cycle. This is illustrated in Fig. 10(b).

Period-Doubling: As the resistance $R$ is decreased further, a period-doubling or pitchfork bifurcation occurs. The limit cycle now closes on itself after encircling $P_+$ twice; this is called a period 2 cycle because a trajectory takes approximately twice the time to complete this closed orbit as to complete the preceding period 1 orbit (see Fig. 10(c)).

Decreasing the resistance $R$ still further produces a cascade of period-doubling bifurcations to period 4 (Fig. 10(d)), period 8, period 16, and so on until an orbit of infinite period is reached, beyond which we have chaos (see Fig. 10(e)). This is a Spiral-Chua strange attractor.\(^3\)

The Spiral-Chua attractor in Fig. 10(e) looks like a ribbon or band that is smoothly folded on itself; this folded band

\(^3\)An attractor is a stable steady-state solution of a dynamical system. An attractor is called strange or chaotic if it contains a transversal homoclinic orbit [1].
Periodic Windows: Between the chaotic regions in the parameter space of Chua's circuit, there exist ranges of the bifurcation parameter $R$ over which stable periodic motion occurs. These regions of periodicity are called periodic windows. Periodic windows of periods 3 and 5 are readily found in Chua's circuit. These periodic limit cycles undergo period-doubling bifurcations to chaos as the resistance $R$ is decreased. Fig. 11(a) shows a period 3 window, so called because the trajectory encircles the outer equilibrium point $P_+$ three times before closing on itself. Fig. 11(b) shows a period 6 orbit that results from a period-doubling bifurcation of this period 3 limit cycle.

Spiral-Chua Attractor: Fig. 12 shows three views of another simulated Spiral-Chua strange attractor. Fig. 12(b) is a view along the edge of the outer complex eigenplanes $E^c(P_+)$ and $E^c(P_-)$; notice how trajectories in the $D_1$ region are compressed toward the complex eigenplane $E^c(P_+)$ along the direction of the stable real eigenvector $E'(P_+)$ and that they spiral away from the equilibrium point $P_+$ along $E'(P_+)$. When a trajectory enters the $D_0$ region through $U_1$, it is twisted around the unstable real eigenvector $E'(0)$ and returned to $D_1$.

Fig. 12(c) shows clearly that when the trajectory enters $D_0$ from $D_1$, it crosses $U_1$ above the eigenplane $E'(0)$. The trajectory cannot cross through this eigenplane; therefore, it must return to the $D_1$ region.

Double-Scroll Chua Attractor: Because we chose a nonlinear resistor with a symmetric nonlinearity, every attractor that exists in the $D_1$ and $D_0$ regions has a counterpart (mirror image) in the $D_{-1}$ and $D_0$ regions. As the coupling resistance $R$ is decreased further, the Spiral-Chua attractor “collides” with its mirror image, and the two merge to form a single compound attractor called a double-scroll Chua strange attractor [2], as shown in Fig. 13.

Once more, we show three views of this attractor in order to illustrate its geometrical structure. Fig. 13(b) is a view of the attractor along the edge of the outer complex eigenplanes $E^c(P_+)$ and $E^c(P_-)$. Upon entering the $D_1$ region from $D_0$, the trajectory collapses onto $E'(P_+)$ and spirals away from $P_+$ along this plane.
produces more regions of chaos, interspersed with periodic windows. Eventually, for a sufficiently small value of $R$, the unstable saddle trajectory [2] that normally resides outside the stable steady-state solution collides with the double-scroll Chua attractor, and a boundary crisis [13] occurs. After this, all trajectories become unbounded. While an unbounded trajectory can occur in a computer simulation, the real world behaves slightly differently, as we shall see.

**Characteristics of Chaos**

**Sensitive Dependence on Initial Conditions:** Consider once more the double-scroll Chua attractor shown in Fig. 13. Two trajectories starting from distinct, but almost identical, initial states in $D_1$ will remain close together until they reach the separating plane $U_1$. Imagine that the trajectories are still close at the knife-edge, but that one trajectory crosses into $D_0$ slightly above $E'(0)$ and the other slightly below $E'(0)$. The former trajectory returns to $D_1$, and the latter crosses over to $D_{-1}$; their "closeness" is lost.

The time-domain waveforms $V_1(t)$ for two such trajectories are shown in Fig. 14. These are solutions of Chua's oscillator with the same parameters as those in Fig. 13; the initial conditions are $(I_3, V_2, V_1) = (1.810mA, 222.014mV, -2.286V)$ (solid line) and $(I_3, V_2, V_1) = (1.810mA, 222.000mV, -2.286V)$ (dashed line). Although the initial conditions differ by less than 0.01% in just one component ($V_2$), the trajectories diverge and become uncorrelated within 5 ms because one crosses the knife-edge before the other.

This rapid decorrelation of trajectories that originate in nearby initial states, commonly called sensitive dependence on initial conditions, is a generic property of chaotic systems. It gives rise to an apparent randomness in the output of the system and long-term unpredictability of the state.

Because chaotic systems are deterministic, two trajectories that start from identical initial states will follow precisely the same paths through the state space. In practice, it is impossible to construct two systems with identical parameters, let alone to start them from identical initial states. However, recent work by Pecora and Carroll and others [14], [15] has shown that it is possible to synchronize two chaotic systems so that their trajectories remain close. These ideas are now being exploited in secure communication systems. Information modulated onto a "random" chaotic carrier can be demodulated by using a synchronized receiver (see, e.g., [16]–[18]).

**Randomness in the Time Domain:** Fig. 15(a), 15(b), and 15(c) show the voltage waveforms $V_1(t)$ corresponding to the period 1, period 2, and Spiral-Chua attractors in Figs. 10(b), 10(c), and 12, respectively. The period 1 waveform is
periodic; it looks like a slightly distorted sinusoid. The period 2 waveform is also periodic. It differs qualitatively from the period 1 in that the pattern of a large peak followed by a small peak repeats approximately once every two cycles of the period 1 signal; this is why it is called period 2.

In contrast to these periodic time waveforms, $V_1(t)$ for the Spiral-Chua strange attractor is quite irregular and does not appear to repeat itself in any observation period of finite length. Although it is produced by a third-order deterministic differential equation, the solution looks "random."

**Broadband Power Spectrum:** Every periodic signal may be decomposed into a Fourier series—a weighted sum of sinusoids at integer multiples of a fundamental frequency [19]. Thus, a periodic signal appears in the frequency domain as a set of spikes at the fundamental frequency and its harmonics. The amplitudes of these spikes correspond to the coefficients in the Fourier series expansion. The Fourier transform is an extension of these ideas to aperiodic signals; one considers the distribution of the signal's power over a continuum of frequencies rather than on a discrete set of harmonics [19], [20].

The distribution of power in a signal $x(t)$ is most commonly quantified by means of the power density spectrum, often simply called the power spectrum. The simplest estimator of the power spectrum is the periodogram [20], [21], which, given $N$ uniformly spaced samples $x(m/f_s)$, $m = 0, 1, \ldots, N - 1$ of $x(t)$, yields $N/2 + 1$ numbers $P(nf_s/N), n = 0, 1, \ldots, N/2$, where $f_s$ is the sampling frequency.

If one considers the signal $x(t)$ as being composed of sinusoidal components at discrete frequencies, then $P(nf_s/N)$ is an estimate of the power in the component at frequency $nf_s/N$. By Parseval’s theorem, the sum of the power in each of these components equals the mean-squared amplitude of the $N$ samples of $x(t)$ [21], [22].

If $x(t)$ is periodic, then its power will be concentrated in a dc component, a fundamental frequency component, and harmonics. In practice, the discrete nature of the sampling process causes power to "leak" between adjacent frequency components; this leakage may be reduced by "windowing" the measured data before calculating the periodogram [20], [21]. In the following discussion, we consider 8192 samples of $V_2(t)$ recorded at 200 kHz; leakage is controlled by applying a Welch window [21] to the data.

We remarked earlier that the period 1 time waveform corresponding to the attractor in Fig. 10(b), is almost sinusoidal; we expect, therefore, that most of its power should be concentrated at the fundamental frequency. The power spectrum of the period 1 waveform $V_2(t)$ shown in Fig. 16(a) consists of a sharp spike at approximately 3 kHz and higher harmonic components that are over 30 dB less than the fundamental.

Because the period-2 waveform repeats roughly once every 0.67 ms, this periodic signal has a fundamental frequency component at approximately 1.5 kHz (see Fig. 16(b)). Notice, however, that most of the power in the signal is concentrated close to 3 kHz.
The Spiral-Chua attractor is qualitatively different from these periodic signals. The aperiodic nature of its time-domain waveforms is reflected in the broadband noise-like power spectrum (Fig. 16(c)). No longer is the power of the signal concentrated in a small number of frequency components; rather, it is distributed over a broad range of frequencies. This broadband structure of the power spectrum persists even if the spectral resolution is increased by sampling at a higher frequency $f_s$.

The chaotic time waveform due to motion on the double-scroll Chua strange attractor also possesses a broad noise-like power spectrum, as shown in Fig. 16(d).

**Laboratory Experiment: Chua's Circuit**

In this experiment, we demonstrate the concepts of multiple equilibria, bistability, limit cycles, and chaos. We examine Hopf and period-doubling bifurcations, eventual passivity, and a boundary crisis.

**Practical Realization of Chua's Circuit:** Chua's circuit can be realized in a variety of ways by using standard or custom-made electronic components. Since all of the linear elements (capacitor, resistor, and inductor) are readily available as two-terminal devices, our principal concern here is with circuitry to realize a nonlinear resistor $N_R$ with the prescribed DP characteristic (shown in Fig. 17).

This line of research was initiated in the mid-1960s, when Chua developed a theory of nonlinear circuit synthesis and realized that such a theory would be academic unless one was allowed to use two-terminal nonlinear resistors with any prescribed $v-i$ characteristics. This in turn motivated the development of systematic synthesis procedures for two-terminal nonlinear resistors [25], [26], [27], [28]. The term Chua diode [29] will henceforth be used to denote any two-terminal nonlinear resistor with a piecewise-continuous DP characteristic synthesized by using standard circuit elements.

Several implementations of Chua diodes with three-segment odd-symmetric piecewise-linear DP characteristics already exist in the literature; these use operational amplifiers (op amps) [7], diodes [6], and transistors. A systematic procedure for synthesizing precision piecewise-linear Chua diodes with independently adjustable slopes and breakpoints is described in [30]. Recently, a single-chip integrated circuit (IC) realization of a Chua diode using operational transconductance amplifiers has been reported [31], [32] and an entire monolithic Chua's circuit has been fabricated [33].

In this section, we describe a practical implementation of Chua's circuit that uses two op amps and six resistors to implement the Chua diode [29]. This robust circuit is intended for demonstration, research, and educational purposes. While it may appear more complicated than earlier implementations in that the nonlinear resistor comprises two op amps, it is possible to buy two op amps in a single package. Thus, our circuit uses a minimum number of discrete components: a pair of op amps and six resistors to implement the Chua diode, two capacitors, an inductor, and a variable resistor.

**Circuit Description:** Fig. 18 shows a practical implementation of Chua's circuit using two op amps and six resistors to implement the Chua diode $N_R$. A complete list of components is given in Table I.

In addition to the components listed, we recommend that two bypass capacitors of at least 0.1 $\mu$F each should be connected between the power supplies and ground, as close to the op amps as possible. The purpose of these capacitors is to maintain the power supplies at a steady dc voltage.

The op amp subcircuit consisting of $A_1, A_2$ and $R_1-R_6$ functions as a nonlinear resistor $N_R$ with driving-point characteristic as shown in Fig. 19. Using two 9V batteries to power the op amps gives $V^+ = 9V$ and $V^- = -9V$. From measurements of the saturation levels of the AD712 outputs, $E_{sat} \approx 8.3V$, giving $E \approx 1V$. With $R_5 = R_3$ and

---

**TABLE I**

**COMPONENT LIST FOR THE CIRCUITS USED IN PARTS I AND II OF THIS PAPER**

<table>
<thead>
<tr>
<th>Element</th>
<th>Description</th>
<th>Value</th>
<th>Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_1$</td>
<td>Op amp ($\frac{1}{2}$ AD712, TL082, or equivalent)</td>
<td>$A_2$</td>
<td>Op amp ($\frac{1}{2}$ AD712, TL082, or equivalent)</td>
</tr>
<tr>
<td>$C_1$</td>
<td>Capacitor</td>
<td>10 nF</td>
<td>$\pm 5%$</td>
</tr>
<tr>
<td>$C_2$</td>
<td>Capacitor</td>
<td>100 nF</td>
<td>$\pm 5%$</td>
</tr>
<tr>
<td>$R$</td>
<td>Potentiometer</td>
<td>2 k$\Omega$</td>
<td></td>
</tr>
<tr>
<td>$R_1$</td>
<td>$\frac{1}{2}$ W Resistor</td>
<td>3.3 k$\Omega$</td>
<td>$\pm 5%$</td>
</tr>
<tr>
<td>$R_2$</td>
<td>$\frac{1}{2}$ W Resistor</td>
<td>22 k$\Omega$</td>
<td>$\pm 5%$</td>
</tr>
<tr>
<td>$R_3$</td>
<td>$\frac{1}{2}$ W Resistor</td>
<td>22 k$\Omega$</td>
<td>$\pm 5%$</td>
</tr>
<tr>
<td>$R_4$</td>
<td>$\frac{1}{2}$ W Resistor</td>
<td>2.2 k$\Omega$</td>
<td>$\pm 5%$</td>
</tr>
<tr>
<td>$R_5$</td>
<td>$\frac{1}{2}$ W Resistor</td>
<td>220 $\Omega$</td>
<td>$\pm 5%$</td>
</tr>
<tr>
<td>$R_6$</td>
<td>$\frac{1}{2}$ W Resistor</td>
<td>220 $\Omega$</td>
<td>$\pm 5%$</td>
</tr>
<tr>
<td>$L$</td>
<td>Inductor (TOKO type 10RB or equivalent)</td>
<td>18 mH</td>
<td>$\pm 10%$</td>
</tr>
</tbody>
</table>
passive—the outermost segments (while not necessarily linear as shown here) for sufficiently large 

Fig. 19. Every physically realizable nonlinear resistor \( N_R \) is eventually passive—the outermost segments (while not necessarily linear as shown here) must lie completely within the first and third quadrants of the \( V_{IR} \)-\( I_{RC} \) plane for sufficiently large \( |V_{IR}| \) and \( |I_{RC}| \).

\[ R_S = R_d, \] the nonlinear characteristic is defined by \( G_a = -1/R_3 - 1/R_4 = -50/66 \, \text{mS} \), \( G_b = 1/R_3 - 1/R_4 = -9/22 \, \text{mS} \), and \( E = (R_1 + R_2) \approx 1 \, \text{V} \). [29].

**Eventual Passivity and the Outer Dissipative Segments:** The DP characteristic of the op amp-based Chua diode differs from the desired piecewise-linear characteristic shown in Fig. 17 in that it has five segments, the outer two of which have positive slopes \( G_e = 1/R_5 = 1/220 \, \text{mS} \). Every physical resistor is eventually passive, meaning simply that for a large enough voltage across its terminals, the instantaneous power consumed by a real resistor is positive. For large enough \( |v| \) or \( |i| \), therefore, its DP characteristic must lie only in the first and third quadrants of the \( v-i \) plane. Hence, the DP characteristic of a real Chua diode must include at least two outer segments with positive slopes which return the characteristic to the first and third quadrants (see Fig. 19). From a practical point of view, as long as the voltages and currents on the attractor are restricted to the negative resistance region of the characteristic, these outer segments will not affect the circuit’s behavior.

By definition, every attractor is bounded. Therefore, it is always possible to scale the voltages and currents in the circuit so that any particular steady-state solution lies completely within the inner three segments of the Chua diode’s DP characteristic (see [29] and [30], for example).

The simplified equivalent circuit of Fig. 18 is shown in Fig. 20. We model the real inductor as a series connection of an ideal linear inductor \( L \) and a linear resistor \( R_0 \).

**Experimental Verification of a Voltage-Controlled DP Characteristic:** The DP characteristic of the nonlinear resistor \( N_R \) can be measured in isolation by means of the circuit shown in Fig 21.

Resistor \( R_S \), known as a current-sensing resistor, is used to measure the current \( I_R \) which flows into the nonlinear resistor \( N_R \) when a voltage \( V_{IR} \) is applied across its terminals. An appropriate choice of \( R_S \) in this example is 100 \( \Omega \). Current \( I_R \) flowing in \( R_S \) then causes a voltage \( V_{IR} = -100I_R \) to appear across the sensing resistor. Thus, we can measure the DP characteristic of \( N_R \) by applying a voltage \( V_S \) as shown and plotting \( V_{IR} (\propto I_R) \) versus \( V_S \). This is achieved by connecting \( V_{IR} \) to the \( y \)-input and \( V_S \) to the \( x \)-input of an oscilloscope in \( x-y \) mode. The resulting characteristic for the components listed in the table is shown in Fig 22. Note that we have plotted \( V_{IR} \) versus \( V_S \); this is possible if your oscilloscope permits inversion of the \( y \)-input in \( x-y \) mode.

**Practical Considerations for Op-Amp Based Chua Diodes:** The breakpoints in the Chua diode’s DP characteristic are proportional to the saturation levels of the op amps. The saturation levels in turn are determined by the power supply voltages and by the internal architecture of the op amps. If the levels are different, as they typically are, the resulting DP characteristic will be asymmetric. This results in a double-scroll Chua attractor which has one lobe bigger than the other.

Furthermore, the input offset voltage of an op amp causes a shift in the DP characteristic when it is used to implement a
Fig. 23. Typical experimental bifurcation sequence in Chua's circuit (component values as in Table I) recorded by using a Hitachi VC-6025 Digital Storage Oscilloscope. Horizontal axis V\(_2\) (a)-(h) 200mV/div, (i) 2V/div; vertical axis V\(_1\); (a)-(h) 1V/div, (i) 2V/div. (a) \(R = 1.83k\Omega\), period 1; (b) \(R = 1.82k\Omega\), period 2; (c) \(R = 1.81k\Omega\), period 4; (d) \(R = 1.80k\Omega\), Spiral-Chua attractor.

Chua diode. While asymmetry may be aesthetically unpleasing, it has little effect on the bifurcation sequence or on the nature of the attractor.

If one wishes, the asymmetry due to saturation level mismatch may be corrected by adjusting the positive and negative power supply voltages until symmetry is achieved. For example, the negative saturation level might be 0.7 V less in magnitude than the positive level. This could be corrected by using power supplies of 9 V and -9.7 V instead of ±9 V.

Normally, it is not possible to zero the offset in an 8-pin dual op amp such as the AD712 or the TL082. In fact, we deliberately chose the AD712 because it draws negligible input current, by virtue of its FET input stage, and has a guaranteed maximum input offset voltage of 1.0 mV (AD712K) [34]. If the offset is disturbing, one may substitute for the dual op amp two single op amp equivalents such as the AD711 and TL081; these have offset balancing pins to enable the user to zero the offset voltage.

Steady-State Solutions: A 2-D projection of each steady-state solution may be obtained by connecting \(V_2\) and \(V_1\) to the X and Y channels, respectively, of an X-Y oscilloscope.

Bifurcations and Chaos: By reducing the variable resistor \(R\) in Fig. 18 from 2000 \(\Omega\) toward zero, Chua's circuit exhibits a Hopf bifurcation from dc equilibrium, a sequence of period-doubling bifurcations to a Spiral-Chua attractor, periodic windows, double-scroll Chua strange attractor, and a boundary crisis, as illustrated in Fig. 23.

Notice that varying \(R\) in this way causes the size of the attractors to change: the period 1 orbit is large; period 2 is smaller; the Spiral-Chua attractor is smaller again; and the double-scroll Chua attractor shrinks considerably before it dies. This shrinking is due to the equilibrium points \(P_+\) and \(P_-\).
Fig. 23 (continued).  
(e) $R = 1.797 \Omega$, period 3 window;  
(f) $R = 1.764 \Omega$, Spiral-Chua attractor;  
(g) $R = 1.734 \Omega$, double-scroll Chua attractor;  
(h) $R = 1.524 \Omega$, double-scroll Chua attractor;  
(i) $R = 1.424 \Omega$, large limit cycle corresponding to the outer segments of the Chua diode’s DP characteristic.
moving closer to the origin as \( R \) is decreased. This is easier to see in the simulations. Compare the position of \( P_+ \) in Figs. 10(a) and 13.

**Alternative Bifurcation Sequence:** An alternative way to view a bifurcation sequence is by adjusting \( C_1 \). Fix the value of \( R \) at 1800 \( \Omega \) and vary \( C_1 \); monitor \( V_1 \) and \( V_2 \) as before. The full range of dynamical behaviors from equilibrium through Hopf, and period-doubling bifurcations, periodic windows, Spiral-Chua and double-scroll Chua chaotic attractors can be observed as \( C_1 \) is reduced from 12.0 nF to 6.0 nF. Unlike the \( R \) bifurcation sequence, the size of the double-scroll attractor remains almost constant in the \( C_1 \) bifurcation sequence because the positions of the equilibrium points are independent of \( C_1 \).

**Eventual Passivity and the Big Limit Cycle:** We noted earlier that no physical system can have unbounded trajectories; in particular, any physical realization of a Chua diode is eventually passive. The “unbounded” trajectories that follow the boundary crises are thus limited in amplitude by the power supplies that are used to power the Chua diode, and a large limit cycle results as shown in Fig. 23(i). This effect could of course be simulated by using a five-segment DP characteristic for \( N_R \) as shown in Fig. 19.

**Simulation of Chua’s Circuit**

Our experimental observations and qualitative description of the global dynamics of Chua’s circuit may be confirmed by simulation using a specialized Nonlinear Dynamics simulation package such as INSITE [35], [36], or by employing a customized simulator. All of the computer-generated figures so far in Parts I and II of this tutorial paper were produced by using special-purpose software called “Adventures in Bifurcations and Chaos” (ABC), which was developed specifically to accompany this work. The program (which uses a fourth-order Runge-Kutta integration routine [35]) is written in Microsoft QuickBASIC and runs without compilation on every IBM-compatible computer that has the MS-DOS version 5.0 operating system.

“ABC” simulates three example circuits: the linear and nonlinear parallel RLC circuits described in Part I, and Chua’s oscillator. For the two-dimensional examples, it generates and plots vector fields, time waveforms, and trajectories. In the case of Chua’s oscillator, the program calculates and draws equilibrium points, eigenvalues, eigenspaces, and trajectories. A two-dimensional projection of the three-dimensional dynamics is shown in a state space plot, and the corresponding time waveforms are simultaneously displayed in a time-domain window. The user may change the parameters, initial condition, and viewing angle, as illustrated in Fig. 13. The ability to view the attractor in a variety of orientations, and thus to “walk through” the three-dimensional state space, permits one to visualize readily the geometric structure of the dynamics.

In addition, the software is accompanied by an extensive database of sets of initial conditions and parameters that produce every dynamical behavior that has been reported for Chua’s oscillator: equilibrium points, bifurcation sequences, periodic orbits, homoclinic and heteroclinic orbits [1], and a plethora of chaotic attractors [8]. This library of steady-state solutions has been prepared over several years in collaboration with Leon Chua’s research group at the University of California at Berkeley. It will be maintained and extended as new attractors are discovered.6

**SPICE Simulations**

For electrical engineers who are familiar with the SPICE circuit simulator [37], but perhaps not with chaos, we present a net-list and simulation results for our robust implementation of Chua’s circuit. The AD712 op amps in this realization of the circuit are modeled using Analog Devices’ AD712 macro-model [38]. The TOKO 10RB inductor has a nonzero series resistance which we have included in the SPICE net-list; we measured \( R_0 = 12.5 \Omega \). Node numbers are the same as those in Fig. 18: the power rails are 111 and 222; 10 is the “internal” node of our physical inductor where its series inductance is connected to its series resistance.

A double-scroll Chua attractor results from our SPICE 3e2 simulation using the input deck shown in Fig. 24. This attractor is plotted in Fig. 25.

**Dimensionless Coordinates and the \( \alpha-\beta \) Bifurcation Diagram:** Thus far, we have discussed Chua’s circuit equations in terms of seven parameters \( L, C_2, G, C_1, E, G_a, \) and \( G_b, \) We can reduce the number of parameters by normalizing the nonlinear resistor such that its breakpoints are at \( \pm R_V \) instead of \( \pm E_V \). Furthermore, we may write Chua’s circuit equations (2)-(4) in normalized dimensionless form by making the following change of variables: \( x = V_1/E, \ y = V_2/E, \ z = I_3/(E_G), \) and \( \tau = tG/C_2. \) Thus:

\[
\begin{align*}
\frac{dx}{d\tau} &= \alpha(y - h(x)) \\
\frac{dy}{d\tau} &= x - y + z \\
\frac{dz}{d\tau} &= -\beta y
\end{align*}
\]

Thus:

\[
\begin{align*}
\alpha(y - h(x)) & \quad \text{if} \quad x < -1 \\
\alpha(y - ax) & \quad \text{if} \quad -1 \leq x \leq 1 \\
\alpha(y - bx - (a - b)) & \quad \text{if} \quad x > 1
\end{align*}
\]

where \( a = G_a/G = 1 + G_b/G, \) \( b = G_b/G = 1 + G_a/G, \) \( \alpha = C_2/C_1, \) and \( \beta = C_2/(LG). \) Thus, each set of seven circuit parameters has an equivalent set of four normalized dimensionless parameters \( \{a, b, \alpha, \beta\}. \) If we fix the values of \( a \) and \( b \) (which correspond to the slopes \( G_a \) and \( G_b \) of the Chua diode), we can summarize the steady-state dynamical behavior of Chua’s circuit by means of a two-dimensional \( \alpha-\beta \) diagram.

Fig. 26 shows the two-parameter bifurcation diagram in the \( \alpha-\beta \)-plane with \( a = -1/7 \) and \( b = 2/7. \) In this diagram, each colored region denotes a particular type of steady-state behavior: for example, an equilibrium point, period 1, trajectory, period 2, Spiral–Chua attractor, double-scroll Chua attractor. Typical state-space behaviors are shown in the insets. For clarity, we show chaotic regions in a single color; it should

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6 Contact the author (e-mail address: mpk@midir.ucd.ie) for a free copy of “ABC.”
be noted that these chaotic regions are further partitioned by periodic windows and "islands" of periodic behavior.

To interpret the $\alpha-\beta$ diagram, imagine fixing the value of $\beta = C_2/(L G^2)$ and increasing $\alpha = C_2/C_1$ from a positive value to the left of the curve labeled "Hopf at $P^{\omega_k}$"; experimentally, this corresponds to fixing the parameters $L, C_2, G, E, G_L$, and $G_{\text{m}}$, and reducing the value of $C_1$ (previously, we called this a "$C_1$ bifurcation sequence").

Initially, the steady-state solution is an equilibrium point. As the value of $C_1$ is reduced, the circuit undergoes a Hopf bifurcation when $\alpha$ crosses the "Hopf at $P^{\omega_k}$" curve. Decreasing $C_1$ still further, the steady-state behavior bifurcates from period 1 to period 2 to period 4 and so on to chaos, periodic windows, and a double-scroll Chua attractor. The right edge of the chaotic region is delimited by a curve corresponding to the boundary crisis and "death" of the attractor. Beyond this curve, trajectories diverge toward infinity. Because of eventual passivity in a real circuit, these divergent trajectories will of course converge to a limit cycle in any physical implementation of Chua's circuit.

**Reality of Chaos**

We saw earlier that a chaotic system is characterized by sensitive dependence on initial conditions; Small perturbations of the state grow exponentially with time. The approximation involved in integrating Chua's circuit equations numerically and the effects of small random perturbations due to noise in an experiment produce simulated and experimental trajectories of chaotic systems that are not exact solutions of the state equations. It follows that any claim that a system is chaotic can be made only if accompanied by a rigorous mathematical proof.

In general, it is extremely difficult to prove the existence of chaos in continuous-time systems. However, such a proof has been given for Chua's circuit by Chua et al. [2]. We paraphrase this result as follows:

**Theorem—Mathematical Chaos in Chua's Circuit:** There exist regions in the $(\alpha, \beta)$ parameter space where the motion on a double-scroll Chua attractor is technically equivalent to that generated by a mathematical model of a coin toss—the Bernoulli shift.

This theorem provides the first rigorous proof of chaos (in the sense of Shilnikov) for a physical system whose theoretical behavior agrees with both computer simulations and experimental results.

**III. CONCLUDING REMARKS**

In this two-part tutorial paper, we have guided the reader into the exciting world of nonlinear dynamics in continuous systems. By means of guided examples and experiments, we have studied the concepts of steady-state solutions, equilibrium points, stability bifurcations, local and global dynamics, limit cycles, and chaos.

In Part I, we showed that while the familiar linear parallel RLC circuit is a poor model of sustained oscillation in real systems, it is a useful aid in developing insights into the nature of these systems.
of oscillation. Using the framework of piecewise-linear circuit theory, we showed how the linear RLC circuit could be used to explain the local behavior of more complicated systems. In particular, we inserted a series voltage-controlled nonlinear resistor in the parallel RLC circuit and saw how this forced us to add an additional transit capacitor to the circuit in order that it be well defined. In this way, the linear parallel RLC resonant circuit evolved into Chua's circuit.

In Part II, we have used the tools and insights developed in Part I to explain the geometrical origins of complex dynamics and chaos in Chua's circuit. We have supported these qualitative observations with computer simulations and experiments.

Chaos is characterized by a stretching and folding mechanism. Nearby trajectories of a deterministic dynamical system are pulled apart and folded back together repeatedly to produce complicated bounded nonperiodic motion on a strange attractor. The exponential divergence of trajectories that underlies chaotic behavior, and the resulting sensitivity to initial conditions, lead to long-term unpredictability which manifests itself as randomness in the time-domain and produces a broadband noiselike power spectrum.

While differential equations and mechanical systems provide convenient frameworks in which to examine bifurcations and chaos, electronic circuits are unique in being easy to build, easy to measure, and easy to model. Furthermore, they operate in real time, and parameter values are readily adjusted. Just as the linear parallel RLC resonant circuit is the simplest paradigm for understanding periodic steady-state phenomena in linear circuits, so Chua's circuit presents an attractive paradigm for studying nonperiodic phenomena in nonlinear circuits. The importance of Chua's circuit and its relatives [39], [40], [41], [42], [43] is that they can exhibit every type of bifurcation and attractor that has been reported to date in third-order continuous-time dynamical systems. While exhibiting a rich variety of complex dynamical behaviors, the circuit is simple enough to be constructed and modeled by using standard electronic parts and simulators.

We strongly encourage the reader to simulate, build, and analyze the circuits that we have presented here as aids to understanding the nature of oscillation and complex dynamics.

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REFERENCES


Michael Peter Kennedy, for a photo and biography, please turn to page 656 of this issue of this TRANSACTIONS.