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# Chaos computing: experimental realization of NOR gate using a simple chaotic circuit

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**Abstract**

We report the experimental realization of a simple threshold controller, which clips chaotic dynamics to periods of different orders, in a continuous-time simple analog simulation type chaotic circuit. Further we use this technique to implement the fundamental NOR gate, thus providing a proof-of-principle experiment to demonstrate the universal computing capability to chaotic circuits. The advantage of this particular realization is that it may be simply implemented with monolithic integrated circuits for low-voltage or low-power applications, and thus is of considerable practical significance.


## 1. Introduction

In recent times there has been a new theoretical direction in harnessing the richness of chaos, namely, the exploitation of chaos to do flexible computations [1–5]. The aim is to use a single chaotic element to emulate different logic gates and perform different arithmetic tasks, and further have the ability to switch easily between the different operational roles. Such a computing unit may then allow a more dynamic computer architecture and serve as ingredients of a general-purpose device more flexible than statically wired hardware.

In this Letter, we will first discuss the experimental realization of a threshold controller that clips the chaos into a simple ordered phenomenon. Then using this control method we will go on to experimentally demonstrate a new and simpler version of the chaos computing scheme [6–8] by directly implementing the fundamental NOR gate with a continuous-time simple analog simulation type chaotic circuit [9,10]. The advantage of this circuit configuration is that, it can be

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easily implemented with monolithic integrated circuits for low-voltage or low-power applications as it uses current-feedback operational amplifiers (CFOAs).

## 2. Controlling of chaos using a threshold control

Consider a single chaotic element, described by the evolution equation: $\mathrm{d}\mathbf{X}/\mathrm{d}t = F(\mathbf{X}; t)$ where $\mathbf{X} = (X_1, X_2, \ldots, X_N)$ are the state variables, and $F$ is a strongly nonlinear function. In this system we choose a variable $X_i$ to be thresholded, i.e., whenever the value of this variable exceeds a critical threshold $X^*$ (i.e., when $X_i > X^*$), it re-sets to $X^*$. The dynamics continues till the next occurrence of $X_i$ exceeding the threshold, when control resets its value to $X^*$ again. So, this controller does not alter the original system in any way, as there is no perturbation on the parameters. Further, no run-time knowledge of $F(X)$ is involved, and no run-time computation is needed to obtain the necessary control. The theoretical basis of this method lies in clipping desired time sequences and enforcing a periodicity on the sequence through the threshold action, which acts as a partial resetting of initial conditions [11]. The effect of this scheme is to limit the dynamic range slightly, i.e., "snip" off small portions of the available phase-space, and this small controlling action is effective in yielding a range of stable behaviours. Chaos is quite advantageous here, as it possess a rich range of temporal patterns that can be clipped to different behaviours. This immense variety is not available from thresholding regular systems.

It can be shown analytically for one-dimensional maps and numerically for multidimensional systems that the threshold mechanism yields stable orbits of all orders by simply varying threshold level [7,11]. But so far limited experimental work has been carried out for the direct verification of this control scheme and its applications for chaos computing concepts. Here we implement the method on a very simple and easily reproducible analog simulation type chaotic circuit. The experimental set-up is the realization of a simple nonlinear third-order ordinary differential equation (ODE), a form which can capture the essential dynamics of double-scroll-like chaotic attractors. The model is given by

$$\dddot{X} = -a\left[\ddot{X} + \dot{X} + X - f(X)\right], \tag{1a}$$

and

$$f(X) = \mathrm{sgn}(X). \tag{1b}$$

The $\mathrm{sgn}(X)$ nonlinearity is odd-symmetrical and the system has a single parameter $(a)$ through which its

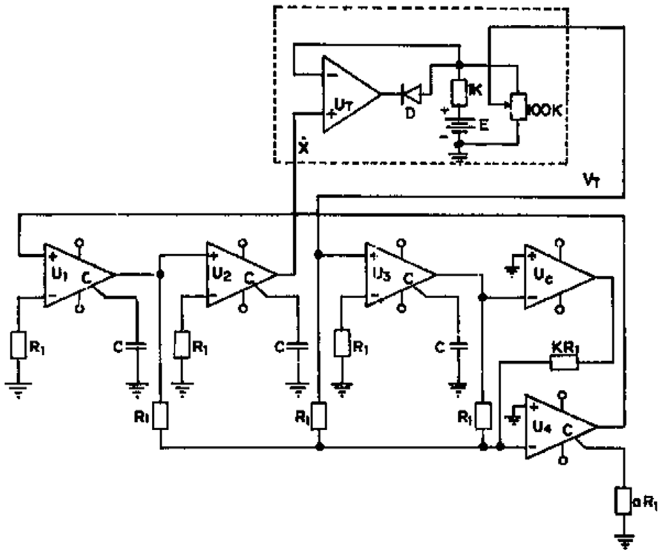


Fig. 1. Circuit implementation of Eq. (1), with the precision clipping control circuit depicted in the dotted box. $V_T$ is the threshold controlled signal.