A Novel Design and Implementation of Full Adder Circuit Using QCA and Qiskit

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1 Introduction

Complementary metal oxide semiconductor (CMOS), which is used to construct integrated circuits in various devices, is one of the most prominent and well-known technologies in today's world as far as the computer chip design business is concerned. In comparison with other MOS technologies available today, CMOS technology offers a lower power dissipation. The number of components on a chip would double every 18 months, according to Gordon Moore's law, which was introduced in 1965 (Kalogeiton et al. 2017). High consumption, low speed, and density beyond 10 nm limit the usage of CMOS technology. As a result, numerous studies have been carried out in order to identify various technologies that could be used to replace traditional CMOS technology (Bahar et al. 2013).

As an alternative to CMOS technology, QCA transistor-less technology, single electron transistor (SET), and carbon nanotube (CNT) are now being utilized. When compared to equivalent implementations using conventional VLSI technology, QCA on the nanoscale has a bright future because of its potential to achieve high performance in terms of clock frequency, device density, and power consumption (Gassoumi et al. 2021).

Basic logic gates, which can be realized using quantum gates, are the fundamental building blocks of logic circuits (Laajimi et al. 2017). Logic circuit implementations have been a focus of quantum system designers (Safoev et al. 2017; Singh et al. 2016). These were potentially constructed using quantum gates with a qubit characterization.

In the proposed work, the quantum gates and instantiation mechanism to build and implement full adder circuit. The fundamental logic circuits can be instantiated to perform high-end logic operations. As a result, the design elements become simpler

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because complicated code is no longer necessary, and these circuits are validated by simulation using the IBM quantum (Thalaimalaivanaraj et al. 2020) simulator.

The QCA design of basic quantum gates such as CNOT and Toffoli, as well as the construction of a full adder employing these gates in the QCA designer tool and IBM Qiskit simulator, is described in this work. The rest of the paper is organized as following, a summary of the QCA technology, quantum computing and working with qubits, the CNOT, Toffoli and full adder design, the simulation results in QCA designer tool, and the simulation results using Qiskit simulator.

Quantum Cellular Automata (QCA) Background

QCA represents data as a charge configuration rather than charge flow. Basic QCA cell has four quantum dots arranged in a square and has two stable states '1' and '0' (Vahabi et al. 2021). When two cells are put next to each other, they tend to assume the same configuration. Basic native gate in QCA is the majority gate with three inputs A, B, and C and one output. Computation happens in the central part. Truth table looks like AND and OR gates in the same gate. Majority gate works as the output is the majority of the input (Singh et al. 2016). Figure 1 shows a basic QCA cell and a QCA wire.

A clock is an important part in QCA that ensures which device holds onto the value and which device assumes its values (Daddala et al. 2015). The clock signals in QCA are generated by an electric field given to the cells, which either raises all of the tunneling barriers between dots within a QCA cell or lowers them all. QCA designer tool provides 4 clocks: Clock 0, Clock 1, Clock 2, and Clock 3. CMOS wires can also supply this electric field to the clock when it is burned under the QCA circuitry.
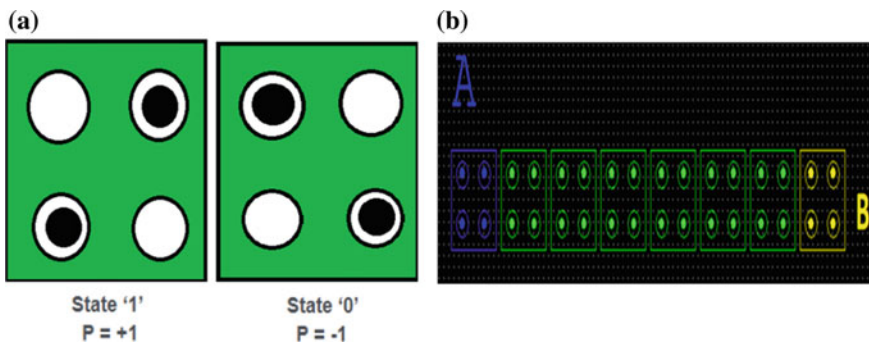

Fig. 1 **a** Basic quantum cell **b** QCA wire

2   Quantum Computing and Qubit

Quantum computing operates by controlling the behavior of particles like electrons and photons in a different way from regular computers. It simulates two bits at one time and is very fluid with non-binary identities or combinations. It can exist in a superposition of zeros and ones with some probability of being zero and some probability of being one. It has an identity on a spectrum.

Qubits use superposition to reduce the number of steps required to complete a computation. When a single phosphorus atom is placed in a silicon crystal immediately close to a transistor, the outermost electron of that atom is used as a qubit. The electron now has a magnetic dipole known as spin, which has two orientations: up and down, which can be represented as a traditional 1 and 0. A high magnetic field has to be provided to discern the energy state of the electron when it is in spin up or spin down. For this, a superconducting magnet is employed. The electron will be in its lowest energy state, with its pin pointing down, and it will need some energy to spin it up. We can place the qubit in a span of state by striking it with a microwave pulse, but it must be of a precise frequency to write information in it (Raman et al. 2022). The frequency is determined by the magnetic field in which the electron is located. As a result, if the pulse is generated at a certain location, a special quantum superposition of the spin up and spin down states is achieved, with a specified phase between the superpositions.

In this work, we use the IBM quantum circuit simulator, which is a collection of high-performance simulators and algorithms. It is a general-purpose simulator, and the optimum method required for the simulation is selected on the basis of the input parameters and circuit provided. Generic code can also be written using the Qiskit library, which could also be used for generating circuits and its relevant components. Qiskit is an open-source software library that covers the entire stack, from the actual interface with IBM Q hardware up to application-level algorithms. As a result, the tool is divided into four libraries that are each called after one of the four ancient elements terra, aqua, aer, and ignis. When integrated, the four Qiskit libraries provide the most comprehensive back-to-back quantum computing software solutions. They all interact with one another through shared data structure elements. The Qiskit software library is completed by an extensive educational collection (Sharma et al. 2022) that spans the entire spectrum of courses for beginners to professionals and from quantum theory to low-level notebook-assisted implementations of specialized quantum circuits.

3   Basic Quantum Gates and Full Adder

(a) **CNOT Gate**

The CNOT gate operates on two qubits. The control qubit is usually the first qubit to be realized. The target qubit is the second of the two qubits. The CNOT gate operates in base states which is expressed as (Fig. 2):

$$f(x, y) = (x, x \oplus y)$$

First input x is control bit; if it is 0, no effect on second bit; and if it is 1, it acts like a NOT gate on second bit.

(b) **Toffoli Gate**

Toffoli gate, commonly known as controlled-controlled NOT gate (CCNOT), is a universal reversible logic gate comprising 3-bit inputs and outputs (Bahar et al. 2013). When the first two bits are both 1, the third bit is inverted; otherwise, all bits remain unchanged (Tables 1 and 2).

(c) **Full Adder**

A full adder is required by most digital circuits in order to execute addition and subtraction. It adds two inputs and a carry in bit, which results in a sum and a carry out bit. As a result (Fig. 3), it has three inputs and two outputs, respectively. The circuit diagram of full adder is shown in Fig. 4.
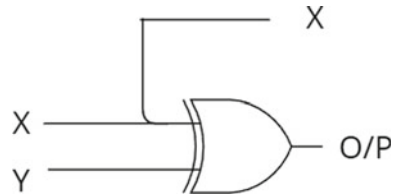
Fig. 2 Logic diagram for CNOT (XOR)

Table 1 Truth table for CNOT (XOR)

Input		Output	
X	Y	X	O/P
0	0	0	0
0	1	0	1
1	0	1	1
1	1	1	0

Table 2 Truth table for Toffoli gate

Input			Output		
X	Y	Z	X′	Y′	Z′
0	0	0	0	0	0
0	0	1	0	0	1
0	1	0	0	1	0
0	1	1	0	1	1
1	0	0	1	0	0
1	0	1	1	0	1
1	1	0	1	1	1
1	1	1	1	1	0

Fig. 3 Logic diagram for Toffoli gate
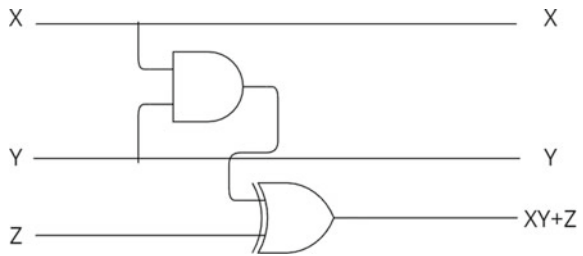
Fig. 4 Logic diagram for full adder circuit
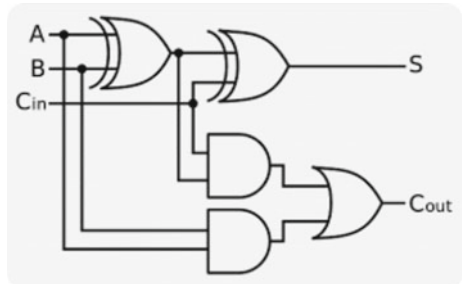
4   Circuit Simulation and Results

(a) **CNOT Gate (XOR Gate)**

The CNOT gate performs a two-qubit operation. As per the simulation graph shown in Fig. 5b, we can observe that whenever both input values are the same that is '0' or '1', then corresponding output obtained is low, and whenever the input values are different (Fig. 5), the output obtained is high (Table 3).
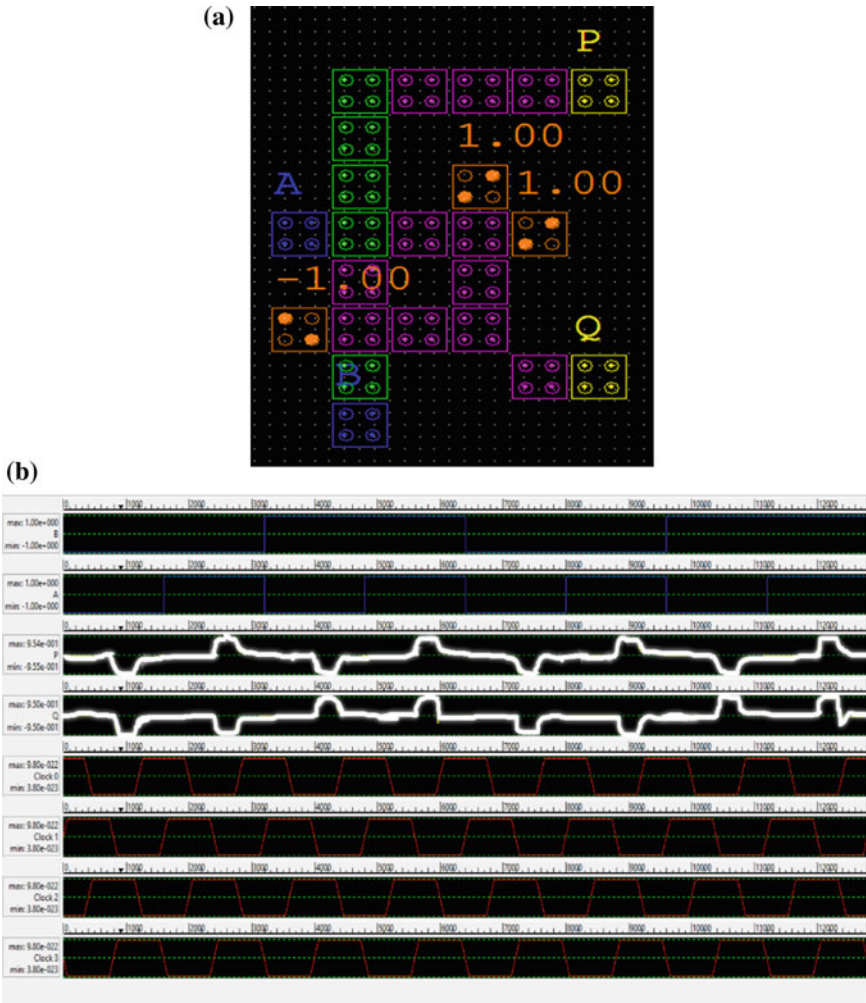
Fig. 5 **a** CNOT gate circuit gate **b** simulation output waveform of CNOT

(b) **Toffoli Gate**

The Toffoli gate performs a three-qubit operation. The circuit works as an AND gate circuit. One qubit is the control qubit, and when the remaining two qubits are the same, the output obtained is high; else, low output is obtained. Implementation of the circuit diagram and corresponding simulation output waveform are shown in Fig. 6a, b.

(c) **Full Adder**

A full adder circuit performs addition of the inputs. It adds three inputs—two operands and a carry bit (Gassoumi et al. 2021; Subashini and Koteeshwari 2018).

Table 3 Full adder truth table

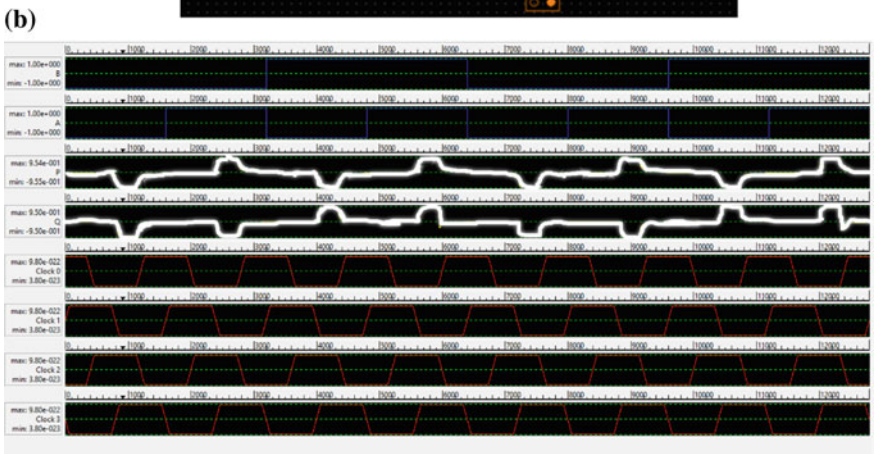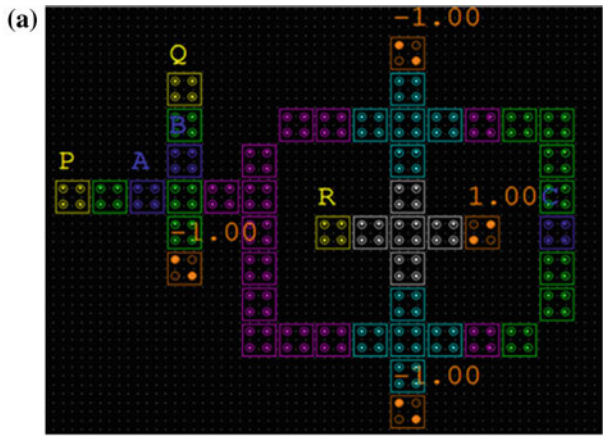| Input			Output	
X	Y	C_{in}	Sum	Carry
0	0	0	0	0
0	0	1	1	0
0	1	0	1	0
0	1	1	0	1
1	0	0	1	0
1	0	1	0	1
1	1	0	0	1
1	1	1	1	1

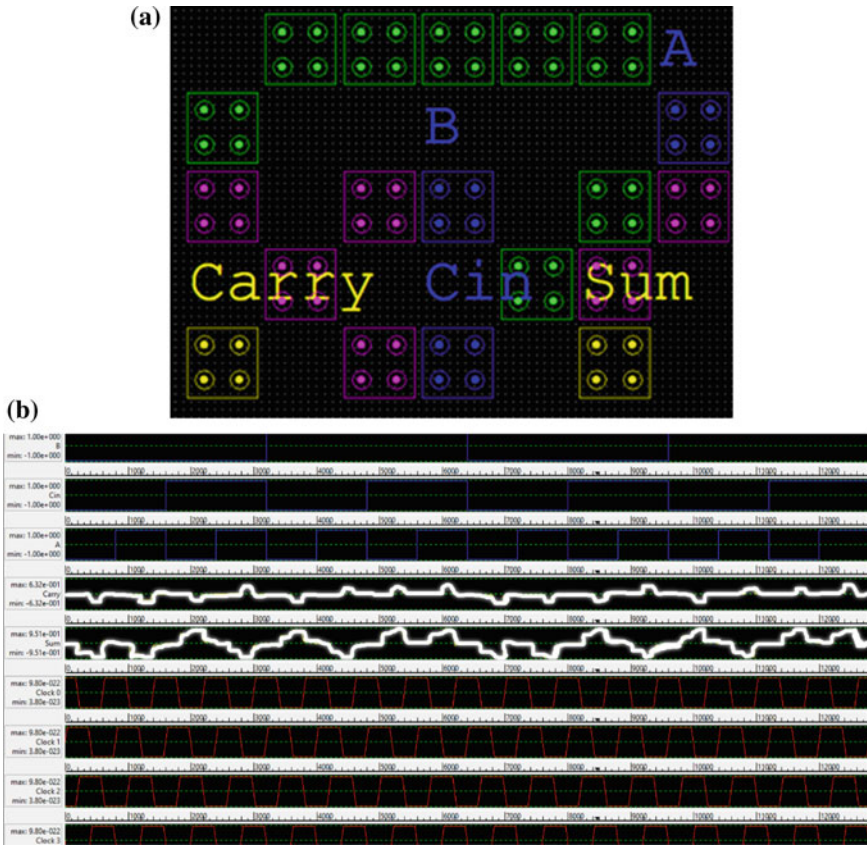**Fig. 6** **a** Toffoli gate circuit implementation **b** simulation output waveform

Fig. 7 **a** Full adder circuit implementation **b** simulation output waveforms

It outputs a sum and a carry bit value. As per the simulation graph, depending on the inputs given, the values of sum and carry in and carry out are carried forward and displayed. In the above figure, the output is shown as a yellow color waveform with carry and sum as the initials (Fig. 7).

5   Qiskit Simulation Results

(a)   CNOT Gate

CNOT gate is simulated using IBM Quantum Composer. It uses 1024 shots to complete the simulation. Before execution, the state is 0000. After simulation, the frequency values 000 and 011 have probability of 522 and 502 (Fig. 8).
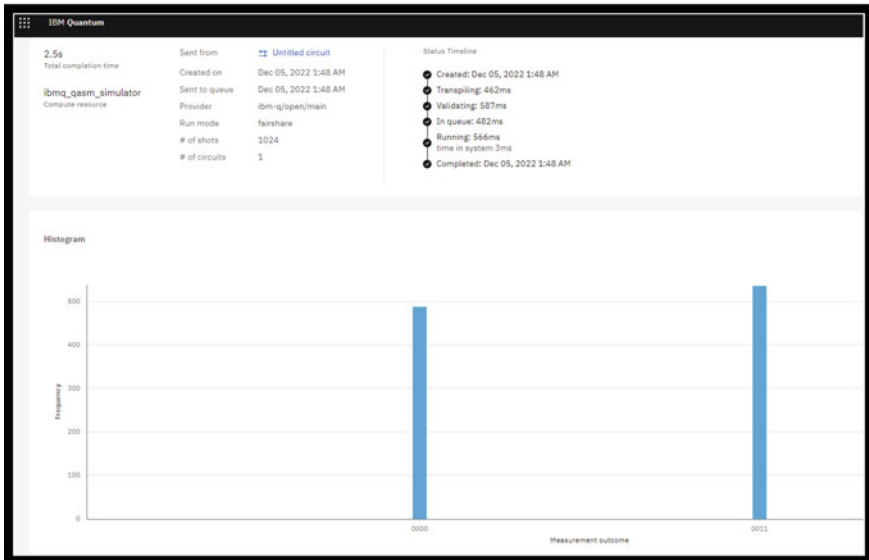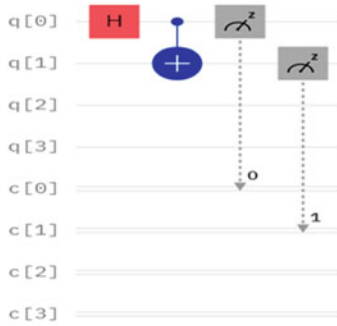
Fig. 8 CNOT gate simulation Qiskit simulator

(b) **Toffoli Gate**

Toffoli gate is simulated using IBM Quantum Composer. It uses 1024 shots to complete the simulation. Before execution, the state is 1110. After simulation, the frequency values 0010 and 1010 have probability of 522 and 502 (Fig. 9).

(c) **Full Adder**

Full adder circuit is simulated using IBM Quantum Composer. It uses 1024 shots to complete the simulation. Before execution, the state is 1001. After simulation, the frequency values 1001 and 1024 have probability of 522 and 502.
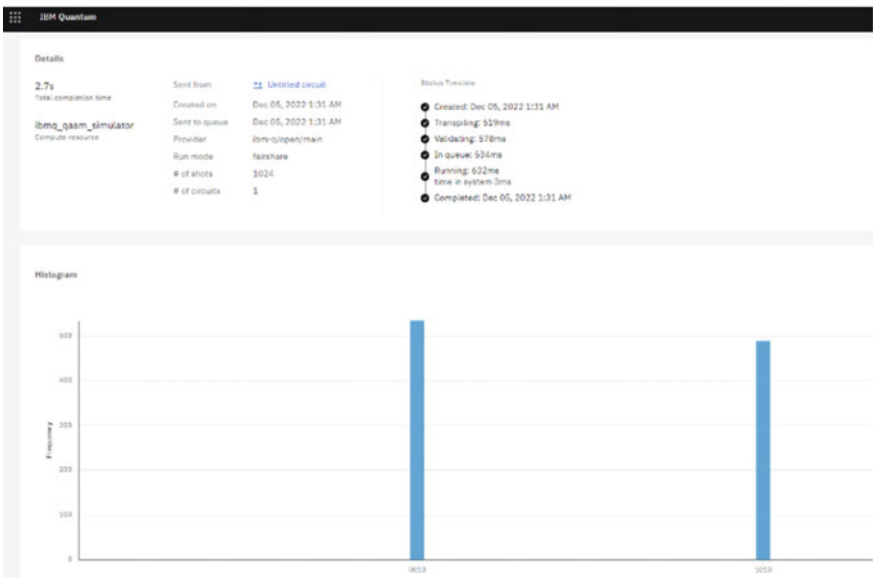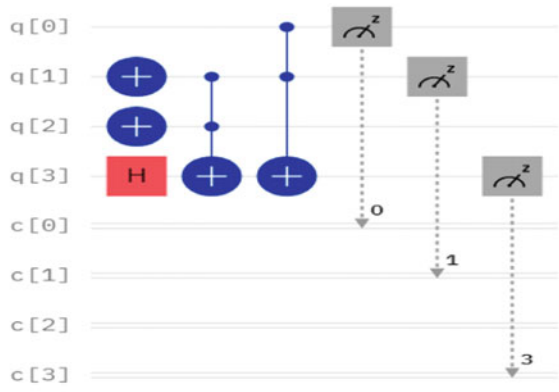
Fig. 9 Toffoli gate simulation Qiskit simulator

The CNOT, Toffoli gate, and full adder are implemented in QCAD and IBM Qiskit simulator (Fig. 10). The below table shows the time taken for simulation in both platforms.

Circuit name	QCAD (in s)	Qiskit (in s)
CNOT gate	1	2.5
Toffoli gate	1	2.7
Full adder circuit	1	2.8

Fig. 10 Full adder implementation using simulation Qiskit simulator

CNOT Gate

Simulator used: IBM Quantum Composer (using Qiskit)
State: 0000 (probability: 51.75781%) (before execution)
   0011 (probability: 48.24219%) (before execution)
Frequency: 000 (488) (after execution)
   011 (536)
No. of shots: 1024 (QASM simulator) 32 qubits

Toffoli Gate

Simulator used: IBM Quantum Composer (using Qiskit)
State: 1110 (probability: 1) (before execution)

Frequency:	0010 (535) (after execution)
	1010 (489)
No. of shots:	1024 (QASM simulator) 32 qubits

Full Adder

Simulator used:	IBM Quantum Composer (using Qiskit)
State:	1001 (probability: 1) (before execution)
Frequency:	1001 (1024) (after execution)
No. of shots:	1024 (QASM simulator) 32 qubits

6   Conclusion

QCA technology is a non-traditional circuit design pattern. CMOS technology drawbacks, primitive growth, and challenges with VLSI chip design are presented in this paper. Simulation is carried out in two software, i.e., QCA and Qiskit. QCA gives the information about the design of the chip, and Qiskit results tell us about the probability occurrence of the qubits. Using the QCAD simulator, we were able to realize the QCA structures of CNOT and Toffoli gates, as well as view the cell structure of a full adder circuit. Simultaneously, we observed similar circuits being executed in a quantum simulator using Qiskit and compared their entire execution time.

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