

A Review of Logic Gates and Their Applications

Dr. Y. Praroopa^{1*}, P. Chenchu Babu²

¹Associate Professor, Department of Mathematics, Sri Durga Malleswara Siddhartha Mahila Kalasala, Vijayawada, Andhra Pradesh, India

²Senior Lecturer, Department of Mathematics, Andhra Loyola College, Vijayawada, A.P.

*Corresponding Author

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ABSTRACT

This paper reviews the fundamental concepts of logic gates and their classical and emerging applications across diverse fields. Logic gates are essential computational units based on Boolean operations and have been implemented in electronic, optical, chemical, and biological systems. The review briefly introduces Boolean and switching logic, followed by a focused discussion of molecular logic gates and their applications in biosensing, ion detection, disease diagnosis, cell imaging, food-safety analysis, pharmaceutical analysis, and synthetic biology. Particular attention is given to DNA-based circuits, fluorescent and electrochemical readouts, aptamer- and DNAzyme-based systems, and CRISPR-associated logic. The review further examines major challenges, including signal leakage, crosstalk, scalability, reproducibility, matrix effects, cost, and translation into point-of-care and clinical applications. Finally, the potential integration of logic-gate systems with nanotechnology and artificial intelligence is highlighted as a promising direction for developing more sensitive, adaptable, and intelligent sensing, diagnostic, and biomedical systems.

Keywords: logic gates; Boolean algebra; switching algebra; molecular logic; DNA computing; biosensors; CRISPR; disease diagnosis; food safety; ion detection

INTRODUCTION

Logic gates implement Boolean operations by mapping one or more inputs to a defined output. They are fundamental functional units of digital circuits and can be implemented using electronic, optical, chemical, or biological components. Truth tables provide a concise representation of input–output relationships [1–5].

As this review focuses on applications rather than serving as a textbook on digital electronics, elementary definitions of logic gates are presented only briefly. The primary focus is on the translation of logical operations into molecular systems, in which ions, nucleic acids, enzymes, biomarkers, and other analytes serve as inputs, while fluorescence, colorimetric, electrochemical, or biological responses serve as outputs [4–8].

LOGIC GATES AND BOOLEAN OPERATIONS

Truth table: A table which lists all the possible combinations of input variables and the corresponding outputs is called a truth table. It shows how the logic circuits output responds to various combinations of logic levels at the inputs.

Inputs and outputs of the logic gates can occur in two levels termed as HIGH, LOW or TRUE, FALSE or ON, OFF or simply 1, 0

Switching algebra:

The Switching algebra is binary, that is, all variables and constants take on one of two values 0,1. Quantities that are not naturally binary must then be coded into binary format. Physically, they may represent a light off or on, a switch up or down, a low voltage or a high one, or a magnetic field in one direction or the other. In digital system, the input may be decimal digit or the output may be letter grade.

OR Gate :

OR Gate may have two or more inputs but only one output. The output assumes the logic state 1, even if one of its input is logic 1 state. Its output assumes the logic state 0 state, only when each one of its input is logic 0 state. OR gate may take output 1, even if one of its input is 1.

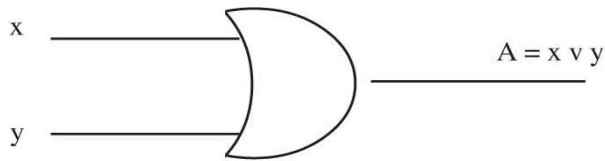


Fig (i)

Figure i. Symbolic representation of a two-input OR gate and its logical output

Truth Table

Input A	Input B	Output
0	0	0
0	1	1
1	0	1
1	1	1

Figure ii. Truth table for the two-input OR gate.

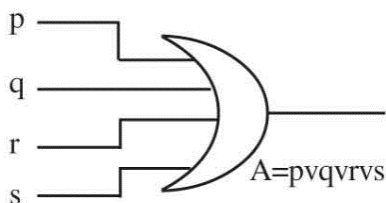


Fig (iii)

Figure iii. Four-input OR-gate representation and Boolean expression.

The output $A = 0$ if and only if all the inputs are 0.

AND Gate :

AND Gate may have two or more inputs but only one output. The output assumes the logic state 1, even if all of its input is logic 1 state. Its output assumes the logic state 0 state, only when one of its input is logic 0 state. AND gate may take output 1, even if each one of its input is 1.

Figure iv. Symbolic representation of a two-input AND gate.

Figure v. Truth table for the two-input AND gate.

Thus the output $A = 1$ when input $p = 1$ and $q = 1$ otherwise $A = 0$ or 1

Such as AND gate may have more than two inputs.

Figure vi. Four-input AND-gate representation and Boolean expression.

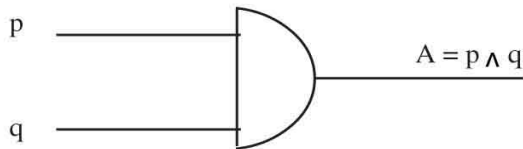


Fig (iv)

Figure iv. Symbolic representation of a two-input AND gate.

2 input AND Gate

A	B	A.B
0	0	0
0	1	0
1	0	0
1	1	1

Figure v. Truth table for the two-input AND gate.

The output $A = 1$ if and only if all the inputs are 1

NOT gate :

NOT gate has only one input and only one output. It is a device whose output is always the complement of its input. That is in Boolean algebra NOT gate is used for $\sim$ operation, the output of the NOT gate assumes the logic 1 state, when its input is in logic 0 state and assumes the logic 0 state, when its input is in logic 1 state

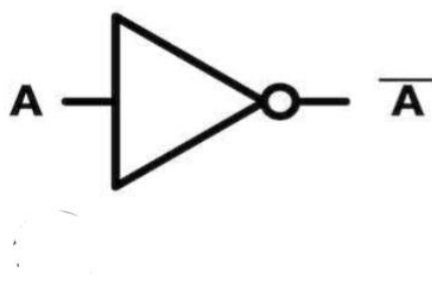


Figure vi.

Logic symbol and truth table for NOT gate

Figure vi. Symbolic representation of a NOT gate.

Figure vii. Symbolic representation of a NOT gate.

2 input NOT gate

A	$\bar{A}$
0	1
1	0

Figure vii.

The value of the output $A = x\sim$ is the complement of the input x .

i.e.,

$$\text{when } x = 0 \quad x\sim = 1$$

$$\text{when } x = 1 \quad x\sim = 0$$

emphasize that a NOT gate can have only one input, whereas the OR and AND gates may have two inputs.

NAND and NOR gates :

The negation of AND gate is called as the NAND gate and the negation of OR gate is called as the NOR gate

There are two additional gates which are equivalent to combinations of the above basic gates.

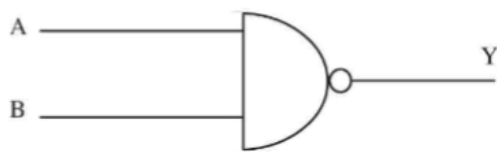


Figure (xiii)

- a. NAND gate, pictured in Figure (xiii) is equivalent to an AND gate followed by a NOT gate.

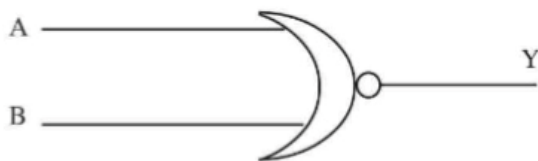


Figure (ix)

- b. NOR gate, pictured in Figure (ix) is equivalent to an OR gate followed by a NOT gate.

Two-input NAND gate

- Boolean expression: $Y = \overline{A \cdot B}$

- Truth table:

A	B	Y
0	0	1
0	1	1
1	0	1
1	1	0

Two-input NOR gate

- Boolean expression: $Y = \overline{A + B}$

- Truth table:

A	B	Y
0	0	1
0	1	0
1	0	0
1	1	0

Figure x. Symbols and truth tables for NAND and NOR gates.

The NAND and NOR gates can actually have two or more inputs just like the corresponding AND and OR gates. Furthermore, the output of a NAND gate is 0 if and only if all the inputs are 1, and the output of a NOR

gate is 1 if and only if all inputs are 0

Figure x. Example Boolean expressions for circuits containing complemented inputs and outputs.

a). $Y = (p \sim q) \sim$

b). $Y = (p \sim \vee q \sim \vee r) \sim$

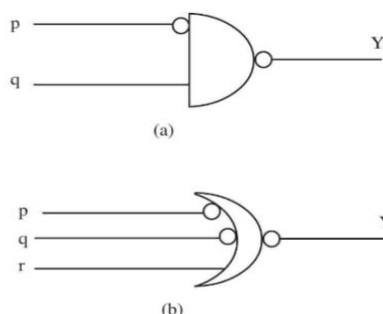


Figure xi. Example Boolean expressions for circuits containing complemented inputs and outputs.

CLASSICAL APPLICATIONS

Logic gates are fundamental building blocks of digital circuits. They perform logical operations on binary inputs to produce a single binary output. Classical applications, such as traffic controllers, security alarm systems, appliance controllers, and warning systems, demonstrate the practical interpretation of truth tables. As these are standard applications in digital electronics, they are briefly summarized here as background information and are not the primary focus of this review [1–3].

MOLECULAR LOGIC GATES IN BIOLOGY, MEDICINE, FOOD SAFETY, AND BIOSENSING

Review Scope and Search Strategy

The review was scoped to peer-reviewed literature on molecular and DNA-based logic gates and their applications in biosensing, ion detection, disease diagnosis, cell imaging, food safety, pharmaceutical analysis, and synthetic biology. The search strategy focused on PubMed, Scopus, and Web of Science, and was supplemented by searches of publisher databases and screening of reference lists. The target publication period was 2007–2026, with particular emphasis on primary research published between 2021 and 2026. The search terms included “molecular logic gate,” “DNA logic gate,” “DNA computing,” “biosensor,” “CRISPR logic gate,” “cancer diagnosis,” “microRNA,” “heavy metal detection,” “food safety,” “pesticide detection,” and “logic-gated drug delivery” [4–8, 14–31].

Disease Diagnosis and Treatment

Molecular logic gates are useful when a single biomarker is insufficiently specific. Liu et al. constructed CRISPR-Cas9-based AND-gate genetic circuits in which two promoter-derived cellular inputs were required to activate the output gene, demonstrating selective identification of bladder-cancer cells in tested cell lines [9]. Sun et al. reported an integrated AND-gate biosensor in which APE1 and miR-222 were the two inputs; an allosteric DNzyme probe coupled recognition, signal transduction, and amplification, while MnO₂ nanosheets provided stimulus-responsive release. The system generated a stronger fluorescence response in target cancer cells than in normal cells and distinguished cell types according to miR-222 expression [10]. Cascaded electrochemical DNA-logic systems have also been developed for combining multiple miRNAs to discriminate pancreatic, breast, and lung cancer signatures [11]. These studies indicate that requiring a combination of biomarkers can improve decision specificity, although larger clinical cohorts, standardized sample processing, and validation in heterogeneous clinical matrices remain necessary.

Cell Imaging and Intracellular Sensing

Fluorescent molecular logic gates are attractive for cell imaging because their optical outputs can be localized spatially. Logic-gated sensors have been demonstrated for metal-ion imaging and intracellular nucleic-acid recognition [4,7,12]. A reversible fluorescent Hg^{2+} chemosensor displayed OR, AND, NOR, and NOT behavior and was also evaluated for live-cell imaging and real samples [13]. The recent APE1/miR-222 AND-gate DNAzyme system used MnO_2 nanosheets as a stimulus-responsive carrier and produced selective fluorescence in target cancer cells [10]. The principal advantage is activation only when the required molecular conditions coexist. Important limitations include background fluorescence, variable intracellular delivery, endosomal trapping, and differences in analyte abundance between cell types.

Food Safety Testing

Food analysis is a demanding test of whether molecular logic can move beyond proof-of-concept sensing. Yan, Shi, and Chen developed a CRISPR-Cas12a platform using acetamiprid (ACE) and atrazine (ATR) as inputs. Aptamer binding initiated amplification and Cas12a generated the fluorescence readout. Detection limits were 2.5 pM for ACE and 0.2 pM for ATR; OR, AND, XOR, and INHIBIT gates were constructed and the platform was evaluated in food samples [14]. Xi et al. developed a dual-output DNA aptamer logic-gate platform for acetamiprid using fluorescence and colorimetric signals with hybridization-chain-reaction amplification; the reported detection limit was 27.7 pM and fruit and vegetable samples were tested [15]. These results demonstrate high analytical sensitivity and multiplexed decision capability. Remaining issues include matrix interference, sample preparation, reagent stability, assay time, and validation against established regulatory methods.

Ion Detection and Environmental Monitoring

Ion detection is one of the most developed application areas for molecular logic. Fluorescent chemosensors can translate ion binding into optical outputs and then combine several inputs into AND, OR, INHIBIT, or related operations [7,16]. A rhodamine-based Hg^{2+} sensor reported detection limits of 32 nM by absorption and 44 nM by fluorescence and used the reversible $\text{Hg}^{2+}/\text{I}^-$ response for INHIBIT logic [17]. A photoinduced-electron-transfer Hg^{2+} sensor reported a detection limit of 7.33×10^{-7} M and demonstrated logic-gate and real-water applications [18]. A quinoline-based Pb^{2+} probe reported a 13 μM detection limit and was evaluated in milk, bioimaging, and an INHIBIT logic-gate configuration [19]. A pyrazoloquinoline sensor implemented OR-type optical logic for Pb^{2+} and Zn^{2+} , with reported detection limits of 1.06×10^{-6} M and 1.07×10^{-6} M, respectively, and was tested in river water [20]. A 2024 seawater study reported detection limits of 16.88 nM for Ag^+ and 5.59 nM for Hg^{2+} and implemented an AND-AND-NOR-AND logic system [21]. Real-sample performance remains sensitive to competing ions, pH, ionic strength, matrix effects, and sensor fouling.

Pharmaceutical Analysis and Logic-Gated Delivery

Molecular logic can integrate multiple chemical or biological conditions before producing an analytical or therapeutic response. DNA- and aptamer-based circuits have been explored for small-molecule recognition, molecular classification, and controlled drug release [4, 8, 22]. A recent advance is logic-gated drug delivery using DNA-drug conjugates. Chen et al. reported affibody-DNA and aptamer-DNA conjugates that recognize two cell-surface biomarkers. Proximity-induced assembly generates an initiator that triggers a hybridization chain reaction involving DNA-drug conjugates. The resulting assemblies undergo endocytosis and release their payload through cathepsin-cleavable linkers [23]. This approach provides a concrete example of an AND-like molecular decision coupled with therapeutic delivery. However, clinical translation requires further evaluation of pharmacokinetics, nuclease stability, immunogenicity, off-target activation, manufacturing complexity, and in vivo efficacy.

Protein Function Regulation and Synthetic Biology

Synthetic biology converts logical relationships among biological signals into programmable cellular behavior. CRISPR-based genetic circuits have been used to implement AND-gate decisions and selectively activate

genes in response to combinations of cellular inputs [9,24]. DNA and RNA logic circuits can process multiple biomarkers before producing fluorescent, electrochemical, or genetic outputs [8,25]. Recent reviews emphasize the integration of CRISPR control, RNA regulators, cell-free systems, and programmable biosensors for healthcare and point-of-care applications [26,27]. The main advantages are programmability and modularity; limitations include host-cell burden, circuit leakage, expression variability, dependence on cellular context, and reproducibility across laboratories.

Summary of Representative Molecular Logic-Gate Applications

Logic gates provide a common framework for converting multiple inputs into defined outputs, and molecular implementations extend this concept to chemical and biological systems. The literature reviewed here demonstrates that DNA, aptamers, DNazymes, fluorescent chemosensors, CRISPR systems, and electrochemical platforms can implement logic operations for disease diagnosis, cell imaging, food-safety analysis, ion detection, pharmaceutical analysis, and synthetic biology. Representative studies demonstrate both quantitative analytical performance and increasingly sophisticated decision-making architectures. Nevertheless, signal leakage, crosstalk, scalability, matrix effects, reproducibility, cost, and clinical and field-level translation remain significant challenges. Future progress will depend on the development of robust multiplexed circuits, standardized validation protocols, portable readout systems, and the integration of CRISPR and nanotechnology, along with careful coupling of molecular computation to clinically or environmentally meaningful decisions. Molecular logic gates should therefore be regarded as complementary molecular decision-making components for smart sensing, diagnosis, and targeted intervention.

Logic and logic gates, rooted in Boolean algebra, form the foundation of modern computation and intelligent systems. This review highlights their significant role in diverse real-world applications, including environmental monitoring, biomedical diagnostics, food safety, and biosensing. The analysis demonstrates that logic gates not only enable digital signal processing but also play a crucial role in the design of smart analytical devices and decision-making systems. With continued advancements in pharmaceutical analysis, nanotechnology, biotechnology, and artificial intelligence, the integration of logic circuits into complex analytical frameworks is expected to expand further. Future research should focus on developing efficient and multifunctional logic systems capable of processing complex, real-time data. Such innovations will further strengthen the connection between logic and practical applications, thereby promoting interdisciplinary progress across science and technology.

Summary table:

Application area	Gate type / architecture	Input → output	Key reference	Performance metric
Disease diagnosis	CRISPR-Cas9 AND	Two promoters → gene activation	[9]	Selective activation in tested bladder-cancer cell lines
Cancer-cell imaging	DNAzyme AND	APE1 + miR-222 → fluorescence	[10]	Strong discrimination of target vs normal cells
Multiple-cancer recognition	Cascaded DNA logic	Multiple miRNAs → electrochemical output	[11]	Discrimination of pancreatic, breast, and lung cancer signatures
Food safety	OR/AND/XOR/INHIBIT	ACE + ATR → fluorescence	[14]	LOD: 2.5 pM ACE; 0.2 pM ATR
Food safety	DNA aptamer logic	Acetamiprid → fluorescence/color	[15]	LOD: 27.7 pM
ATP biosensing	AND aptasensor	ATP + DNA → fluorescence	[28]	LOD: 142.6 pM; range 20–400 nM
Hg ²⁺ detection	OR/AND/NOR/NOT	Hg ²⁺ ± EDTA/I [−] → fluorescence	[13,17]	LOD: 44 nM by fluorescence [17]
Hg ²⁺ detection	Logic-gated chemosensor	Hg ²⁺ → fluorescence	[18]	LOD: 7.33 × 10 ^{−7} M

Ag ⁺ /Hg ²⁺ seawater	AND-AND-NOR-AND	Ag ⁺ + Hg ²⁺ → fluorescence	[21]	LOD: 16.88 nM Ag ⁺ ; 5.59 nM Hg ²⁺
Logic-gated delivery	Biomarker AND + HCR	Two surface biomarkers → DNA- drug payload	[23]	Amplified payload delivery; cleavable release

CONCLUSION

This paper reviewed the fundamental concepts of logic gates and their classical applications across diverse fields. Logic gates serve as essential computational units based on Boolean operations and have been extended beyond conventional electronic systems to optical, chemical, and biological platforms. Particular emphasis was placed on molecular logic gates and their applications in biosensing, ion detection, disease diagnosis, cell imaging, food-safety analysis, pharmaceutical analysis, and synthetic biology. DNA-based circuits, fluorescent and electrochemical readouts, aptamer- and DNAzyme-based systems, and CRISPR-associated logic demonstrate the growing potential of these systems for intelligent and selective signal processing. Despite significant progress, challenges such as signal leakage, crosstalk, scalability, reproducibility, matrix effects, cost, and translation to point-of-care and clinical applications remain. Future developments integrating logic-gate systems with nanotechnology and artificial intelligence may further enhance their sensitivity, adaptability, and practical utility, opening new opportunities for advanced sensing, diagnosis, and biomedical applications.

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