

TOWARDS PRECISION ADVERTISING: THE DATA SCIENCE POWERED BY QUANTUM METHODS FOR SMART ADVERTISING ECOSYSTEM

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Abstract. The advent of quantum computing presents a paradigm shift with significant implications for advertising science and data-driven decision-making. This theoretical short note examines the emerging role of quantum computational methods in advertising data science, extending beyond the conventional view of quantum computing as merely providing computational speed advantages. It proposes a conceptual framework in which quantum algorithms may redefine how complex advertising problems are represented, analysed, and solved within contemporary advertising ecosystems. Particular attention is given to potential applications in hyper-personalization, multi-touch attribution modelling, and creative optimization, where increasingly complex consumer data require more advanced analytical approaches. The paper also critically considers the theoretical, practical, and ethical challenges associated with integrating quantum methods into advertising research and practice, including technological limitations, data governance, interpretability, and responsible implementation. By mapping the intersection between quantum science and advertising analytics, this paper seeks to stimulate scholarly discussion and establish directions for future interdisciplinary research and theoretical development.

Keywords: *quantum computing, advertising analytics, data science, quantum machine learning, precision advertising*

Introduction

Advertising has historically relied on demographic estimates, mass media monitoring, and intuition-driven creative solutions. The digital revolution, characterized by exponential growth in data generation and computational power, has shifted this paradigm toward the quantitatively rigorous discipline of data science (Malthouse et al., 2024; Brown, 2024; Huh and Malthouse, 2020) and regarded as an interdisciplinary field that uses scientific methods, algorithms, and systems to extract insights from structured and unstructured data (*Figure 1*). As a method for transforming business data into strategic assets, it helps organizations improve revenue, reduce costs, seize opportunities, and enhance customer experience (Banks et al., 2025; Mayernik, 2025; Mike and Hazzan, 2023; Sarker, 2021). Data science proliferation has positioned data science at the core of smart advertising ecosystems, leading scholars like Deighton (2017) to argue that “Data science is disrupting the work of agencies.”

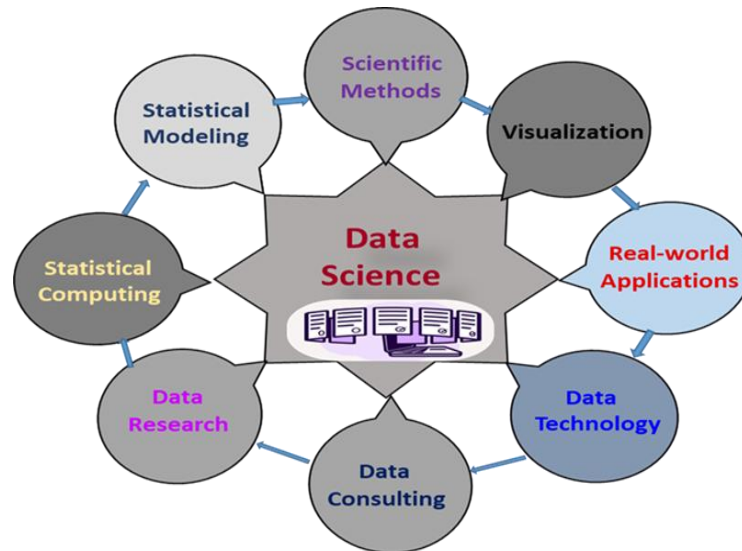


Figure 1. Data science systems and methods.

Results and Discussion

Advertising data science

The contemporary advertising ecosystem is a complex, interconnected network of participants, technologies, data, and transactions that enable digital advertising to function. Advertising data science is fundamentally constrained by the computational limits of classical computing architectures. Tasks such as high-dimensional consumer clustering, real-time bidding (RTB) optimization, and cross-channel attribution strain classical systems, often forcing reliance on approximations of intractable problems (Priya et al., 2025; Huh et al., 2023; De Pelsmacker, 2021). Nonetheless, data science has transformed advertising research by enabling personalization at the individual or micro-segment level (Kumar et al., 2024; Jain et al., 2022). Techniques like clustering algorithms, latent class models, and representation learning identify heterogeneous consumer responses to advertising stimuli (*Figure 2*). A key research contribution lies in linking these data-driven segments to theoretically meaningful constructs, such as consumer preferences, involvement, or decision-making strategies. Consider Netflix, often cited as a benchmark for data science integration in advertising and personalization. By late 2025, reports suggest nearly 45-50% of new sign-ups in available markets were choosing its ad-supported tier. Netflix utilizes data science to integrate ads into the viewing experience seamlessly. Using computer vision, its AI identifies “natural story beats” (e.g., scene transitions) to place ads where they are least disruptive. Natural language processing (NLP) allows for thematic ad matching; for instance, a cooking show might trigger an ad for high-end kitchenware. Furthermore, Netflix utilizes Multi-Armed Bandit (MAB) algorithms to test thousands of thumbnail variations for each user, personalizing the very presentation of content. This approach significantly boosts engagement metrics like the “Watch Start” rate. Additionally, churn prediction and retention models, powered by data science, are estimated to save the company substantial revenue annually by preventing cancellations.



Figure 2. Data science in advertising.

Bridging the literature gap

Despite these advances, traditional computing faces significant challenges in managing the scale and complexity inherent to advertising data. First, the linear scaling of classical algorithms leads to prohibitive increases in processing time and memory requirements for exponentially growing data volumes, hindering real-time analytics (Banks et al., 2025; Eisend and Tarrahi, 2016). Second, datasets with thousands of consumer features suffer from the “curse of dimensionality,” complicating pattern discovery and statistical significance (Prihatiningsih et al., 2025; Sarker, 2021). Third, developing sophisticated models, particularly AI and deep learning networks, demands immense computational resources over prolonged periods (Wright and Schultz, 2025). Consequently, a core tension exists in advertising data science: Statistically optimal methods are often computationally intractable, while computationally feasible methods may be statistically suboptimal. Quantum computing, which harnesses principles of quantum mechanics, e.g., superposition, entanglement (Narayan et al., 2026; Krishnamurthi et al., 2022; Preskill, 2018), holds the potential to revolutionize advertising data science by also addressing these limitations. It promises to process and analyze complex datasets at unprecedented scales and speeds. This paper investigates a pivotal question: How could quantum principles transform the theoretical and applied foundations of advertising data science? We argue that the synergistic intersection of data science and quantum technology represents a potential breakthrough in computational power for advertising science (*Figure 3*), paving the way for a new era of precision advertising that surpasses the capabilities of traditional methods as summarized in *Table 1*.

Table 1. Comparison between traditional and precision advertising paradigm.

Feature	Traditional Advertising (e.g., TV, Billboards)	Precision Advertising (e.g., Social Ads)
Core Nature	An advertising strategy and philosophy. It's the “what” and the “why.”	A technical discipline and function. It's the “how.”
Primary Goal	To increase advertising effectiveness by delivering	To extract actionable insights, build predictive

Key Activities	hyper-relevant, personalized experiences to specific audiences or individuals. Defining target audiences, crafting personalized messages, choosing channels, executing campaigns, measuring advertising CPT.	models, and solve complex advertising problems using data. Data cleaning, statistical analysis, machine learning model development, A/B test design, algorithm creation, data visualization.
Main Output	Targeted campaigns, personalized content, improved customer journeys, higher ROI on advertising spend.	Reports, dashboards, predictive scores (e.g., churn probability), segmentation models, recommendation engines, optimization algorithms.
Ownership/Team	Advertising department and ad agency (Campaign Specialists). They set the objectives.	Data Science/Analytics Team (often centralized or embedded). They provide the capabilities.
Analogy	The navigation system and destination. It decides <i>where</i> to go (which customer to target) and <i>why</i> (to sell product X).	The engine, sensors, and technologies provide more precise <i>power, data, and calculations</i> to find the most efficient route.
Targeting	Broad, demographic-based (e.g., “women 25–54”).	Hyper-specific, behavioral and interest-based.
Message	One static message for a mass audience.	Personalized, dynamic creative optimization.
Placement	Fixed (specific TV show, magazine).	Real-time, based on user behavior and context.
Measurement	Estimated reach, brand lift surveys.	Granular, data-driven (clicks, conversions, ROI).
Cost Model	High upfront cost based on estimated reach.	Often performance-based (e.g., pay-per-click).

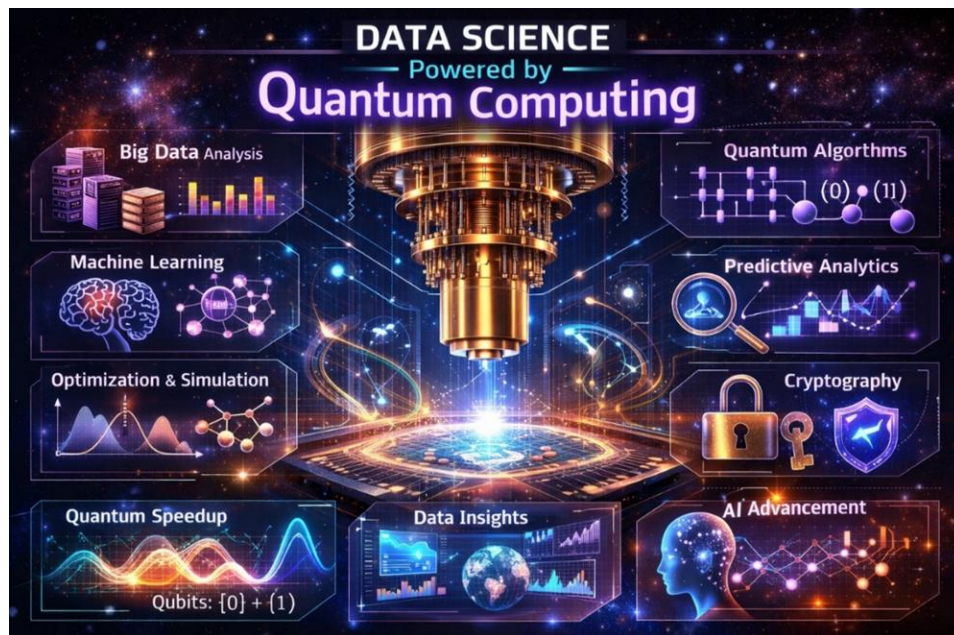


Figure 3. Data science powered by quantum computing.

This short note's overarching goal is to explore the potential for quantum computing to overcome current advertising data science limitations and serve as a transformative tool for advertising research. We posit that quantum methods will impact advertising across several conceptual axes, summarized in *Table 2*.

Table 2. Potential quantum-powered transformations in advertising ecosystems.

Advertising Function	Quantum-Powered Transformation	Potential Practical Impact
Real-Time Bidding (RTB)	Simultaneous evaluation of millions of bid opportunities and user-context variables for optimal micro-decisions.	Maximizes campaign ROI by identifying the best possible impression in milliseconds.
Hyper-Personalized Targeting	Real-time processing of a user's complete cross-channel data footprint to model individual behavior with unprecedented depth.	Enables true “audiences of one” with dynamically tailored creative and messaging.
Cross-Channel Optimization	Solves complex global optimization for allocating budgets and creative variants across dozens of platforms.	Dynamically shifts spend and creative in real-time across the entire media mix for maximum effect.
Predictive Analytics and Attribution	Models non-linear customer journeys with thousands of touchpoints for accurate	Provides near-perfect attribution modeling and precise trend

	attribution and forecasting.	forecasting, minimizing wasted spend.
Ad Fraud Prevention	Analyzes massive, real-time bidstream data to identify sophisticated, evolving fraud patterns.	Dramatically reduces financial losses by detecting novel fraudulent schemes as they emerge.

A framework for quantum-enhanced advertising data science

We propose that quantum computing's impact will extend across three foundational layers of advertising data science: representation, optimization, and simulation. **Quantum Representation of Consumer State:** A classical consumer profile is typically a vector in a high-dimensional feature space. A quantum-inspired model can represent a consumer as a superposition of many potential states (e.g., intents, preferences, contexts) simultaneously. This “quantum cognitive model” aligns with the inherent ambiguity and context-dependency of human decision-making (Busemeyer and Bruza, 2012). It allows for a more nuanced, probabilistic representation that collapses to a specific observed state upon a measurement event, such as an ad exposure or click. **Quantum Optimization for Core Advertising Problems:** Core advertising challenges are often combinatorial and NP-hard: selecting the optimal combination of audience segment, creative asset, media, and bid price from billions of possibilities. Quantum algorithms like the Quantum Approximate Optimization Algorithm (QAOA; Biamonte et al., 2017) and Grover's search offer potential quadratic-to-exponential speed-ups for such problems. This could enable the exploration of solution spaces currently inaccessible to classical computers, revolutionizing tasks like real-time bidding portfolio optimization and multi-media budget allocation.

Quantum Machine Learning for Pattern Recognition: Quantum kernels and variational quantum circuits can be trained to identify complex, non-linear patterns in consumer data that are difficult for classical models to capture (Biamonte et al., 2017). This capability could revolutionize: **Micro-Moment Prediction:** Modeling fleeting, context-dependent purchase intents from sparse and noisy data streams. **Advanced Creative Analysis:** Performing quantum natural language processing (QNLP) on user-generated content and ad copy to uncover latent semantic structures and sentiment. **Quantum Simulation and Game Theory:** The advertising ecosystem is a multi-agent environment involving advertisers, platforms, and consumers. Quantum game theory provides frameworks where agents' strategies can be entangled, offering novel models for cooperative and competitive bidding in programmatic auctions (Narayan et al., 2026). Furthermore, quantum computers are natural simulators of quantum systems. This capability could be harnessed to run high-fidelity, agent-based models of consumer networks, simulating information diffusion, sentiment cascades, and the impact of advertising shocks in synthetic yet realistic market environments.

Critical challenges and research frontiers

The path to quantum advantage in advertising has some hurdles. Notable challenges include: **Hardware Limitations:** Current Noisy Intermediate-Scale Quantum (NISQ) devices lack the qubit count, stability (coherence time), and error correction for practical advertising applications (Narayan et al., 2026; Preskill, 2018). **Hybrid quantum-classical algorithms** represent the most viable near-term path. **Data Encoding:** The fundamental challenge of efficiently loading classical “big data” into a quantum state (a prerequisite known as quantum RAM or QRAM) remains largely unsolved. **Interpretability and Theory Building:** Quantum machine learning models can be profound “black boxes.”

Marketing scholars must lead in developing interpretable quantum models that generate falsifiable hypotheses about consumer behavior, moving beyond mere prediction to explanation. Ethical and Privacy Implications: Quantum-amplified analytics could infer sensitive consumer attributes with unprecedented accuracy, raising severe privacy concerns. Furthermore, quantum computers threaten current encryption standards, necessitating the adoption of quantum-safe cryptography to secure advertising data pipelines (Krishnamurthi et al., 2022).

Extending the advertising data science research agenda

An important direction for future advertising research is the development of hybrid quantum-classical approaches rather than assuming an immediate replacement of conventional data science. Current quantum systems remain within the NISQ era, in which noise, limited coherence, and restricted computational resources constrain the scale of practical applications (Preskill, 2018). Consequently, quantum computing may initially complement rather than replace established advertising analytics. Classical systems could continue performing data preparation, feature engineering, visualization, and routine prediction, while quantum processors are selectively employed for computationally intensive optimization or pattern-recognition problems. Such an approach provides a more realistic pathway through which advertising researchers can investigate quantum advantage without abandoning mature classical analytical infrastructures. Another research opportunity concerns the relationship between computational capability and advertising theory. The increasing availability of large and heterogeneous datasets does not automatically produce stronger theoretical explanations. Computational advertising requires researchers to connect sophisticated analytical techniques with meaningful questions about consumers, media, advertising effectiveness, and decision-making (Huh et al., 2023; Huh and Malthouse, 2020). Quantum-enhanced models therefore should not be evaluated solely according to computational speed or predictive accuracy. Their scholarly contribution will also depend on whether they enable researchers to identify previously inaccessible relationships, test advertising theories under more complex conditions, and explain heterogeneous responses across consumers and contexts.

The quality of advertising data will remain equally important in a quantum-enhanced environment. Greater computational power cannot compensate automatically for biased, incomplete, poorly measured, or unrepresentative data. Banks et al. (2025) emphasize the importance of addressing bias throughout the life cycle of data science projects, while Malthouse et al. (2024) highlight the importance of data quality when computational research relies on emerging data sources. Therefore, future quantum advertising research must incorporate rigorous procedures for data validation, bias assessment, measurement quality, and reproducibility. Otherwise, quantum acceleration may simply allow inaccurate or biased models to produce problematic results more rapidly. Quantum-enhanced advertising also creates opportunities for a deeper reconsideration of personalization. Contemporary data science already enables targeted advertising through the analysis of behavioral and social data (Kumar et al., 2024; Jain et al., 2022). Quantum approaches may potentially extend this capability by examining substantially larger combinations of contextual variables and alternative consumer states. However, greater personalization should not be equated automatically with greater advertising effectiveness. Researchers will need to determine the conditions under which increasingly granular targeting improves consumer experience and the

conditions under which it generates perceptions of surveillance, intrusiveness, or manipulation. This creates an important theoretical frontier connecting computational capability with consumer response and advertising effectiveness.

Finally, the transition toward quantum-enhanced advertising data science should be understood as an interdisciplinary research agenda rather than solely a technological development. Data science itself integrates computational, analytical, and domain-specific perspectives (Mayernik, 2025; Mike and Hazzan, 2023; Sarker, 2021). The incorporation of quantum computing further expands this interdisciplinary requirement by bringing together advertising researchers, data scientists, computer scientists, quantum specialists, and practitioners. Such collaboration will be essential for translating abstract quantum capabilities into advertising problems that are theoretically meaningful, computationally appropriate, and practically relevant. The most significant contribution of quantum computing to advertising may therefore emerge not simply from faster computation, but from its ability to stimulate new models, research questions, and conceptualizations of consumer behavior within increasingly complex advertising ecosystems.

Conclusion

Quantum computing is not merely a technical upgrade; it represents a potential ontological shift for advertising data science (Narayan et al., 2026; Krishnamurthi et al., 2022; Biamonte et al., 2017). It challenges the field to reconceive consumer data, model architectures, and optimization logic (Narayan et al., 2026; Biamonte et al., 2017). While widespread practical deployment may be years away, the time for theoretical and methodological exploration is now (Narayan et al., 2026; Preskill, 2018). We call for interdisciplinary collaborations between advertising scientists, quantum information theorists, and computational social scientists to investigate the following most pressing challenges (Narayan et al., 2026; Huh et al., 2023; Huh and Malthouse, 2020). Develop quantum-native representations of fundamental marketing constructs (e.g., brand perception, customer journey) (Narayan et al., 2026; Biamonte et al., 2017). Formulate core advertising problems (e.g., targeting, attribution) as well-defined quantum circuits and algorithms (Narayan et al., 2026; Biamonte et al., 2017). Proactively establish ethical guidelines and governance frameworks for a future quantum-powered advertising ecosystem (Banks et al., 2025; Krishnamurthi et al., 2022).

A further priority for future research is to determine where genuine quantum advantage can be demonstrated in advertising practice. Researchers should avoid assuming that quantum approaches will automatically outperform classical data science methods. Instead, systematic benchmarking is needed to compare quantum, hybrid quantum-classical, and conventional algorithms across advertising tasks such as targeting, segmentation, attribution, bidding, and personalization. Such evaluations should consider not only computational speed, but also predictive accuracy, scalability, robustness, interpretability, and resource requirements (Narayan et al., 2026; Banks et al., 2025; Biamonte et al., 2017). Another important direction concerns the quality and structure of advertising data used in quantum-enhanced models. Advertising datasets are often heterogeneous, incomplete, high-dimensional, and potentially biased, particularly when they are collected from multiple digital platforms and consumer touchpoints. Greater computational capacity does not automatically resolve these limitations. Future studies should therefore investigate how data quality, bias, feature representation, and

measurement validity influence the effectiveness of quantum-enhanced advertising analytics (Banks et al., 2025; Malthouse et al., 2024; Sarker, 2021). This will be essential to ensure that any claimed quantum advantage is based on reliable data rather than computational complexity alone.

Future research should also examine the organizational and theoretical implications of integrating quantum technologies into advertising research and practice. The emergence of quantum-enhanced analytics may require new forms of expertise, interdisciplinary training, and collaboration between advertising scholars, data scientists, and quantum computing specialists. At the same time, researchers must continue to connect computational innovation with meaningful advertising theory, ensuring that increasingly sophisticated models contribute to explanation as well as prediction (Narayan et al., 2026; Huh et al., 2023; Huh and Malthouse, 2020). This interdisciplinary development may help establish a more coherent research agenda in which technological capability, theoretical relevance, and practical advertising outcomes evolve together. In sum, the "quantum advantage" in advertising data science will ultimately be defined not just by speed, but by the depth of insight it affords into the complex system of consumer response and behavior (Narayan et al., 2026; Priya et al., 2025; Biamonte et al., 2017). By initiating this dialogue today, advertising academics can embark on a "quantum leap" and contribute to the responsible and effective development of this transformative technology (Narayan et al., 2026; Banks et al., 2025; Huh et al., 2023).

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Conflict of interest

The authors confirm that there is no conflict of interest involve with any parties in this research study.

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