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Cyber-Physical Systems Challenges for UAVs: Defense Industry Insights

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Cyber-Physical Systems Challenges for UAVs: Defense Industry Insights

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Abstract

Objective: This paper identifies the challenges faced by the U.S. Department of Defense (DoD) in advancing Cyber-Physical Systems (CPS) for Unmanned Aerial Vehicles (UAVs). It analyzes focus areas in CPS development and provides strategic guidance for future industry efforts.

Background: Cyber-Physical Systems and UAVs have reshaped modern military operations, supporting critical tasks such as surveillance, reconnaissance, and mission planning. Despite increased budget allocation for Research, Development, Testing, and Evaluation (RDT&E), addressing other nations' threats remains a significant challenge. Also, the confidential nature of defense programs limits the level of detail available in reports, making it difficult for industry stakeholders to identify priority areas and align their efforts effectively with defense objectives.

Methodology: This research analyzes DoD reports, including the Cyber Strategy Summary, budget requests, and RDT&E program data, while also incorporating industry insights. A curiosity-driven approach inspired by the Kern Entrepreneurial Engineering Network (KEEN) was used to evaluate systemic relationships in DoD documents. Epistemic curiosity guided the identification of resource patterns, while diverse curiosity aligned challenges with critical defense objectives. Data visualization tools were used to present findings clearly.

Results: The analysis identifies six challenges in CPS for UAVs. Between them, security, dependability, and sustainability are associated with a great part of the RDT&E budget allocation. While progress has been made, these areas remain essential for addressing current and future threats. Investments in these domains support the DoD Cyber Strategy goals and reflect priority areas in government funding.

Conclusion: To strengthen CPS in UAV technologies, the defense industry must prioritize advanced cybersecurity measures, ensure reliable and continuous operations, and develop sustainable systems for long-term effectiveness. By focusing on security, dependability, and sustainability, next-generation Cyber-Physical Systems can reinforce national defense, counter evolving threats, and maintain the United States' advantage in military operations.

Keywords: KEEN, Cyber-Physical Systems, UAVs, Department of Defense, Strategic Planning

Introduction

Background

The integration of Cyber-Physical Systems (CPS) and Unmanned Aerial Vehicles (UAVs) in modern warfare has transformed how missions are planned and executed. Recent conflicts of the Second Nagorno-Karabakh War[1] and the Ukraine-Russia War[2] highlighted the critical role these technologies play in surveillance, reconnaissance, and tactical operations. Also, these conflicts highlight the need to enhance current military CPS technologies in UAVs, as adversaries adopt strategies that are more sophisticated.

The U.S. Department of Defense (DoD) has significantly increased its budget requests in recent years[3, 4, 5, 6, 7, 8]. A substantial portion of this funding is allocated to Research, Development, Testing, and Evaluation (RDT&E) to maintain the U.S. technological advantage. For FY2025, shown in Figure 1 (left), the DoD requested $849.8 billion[8], an 18% increase compared to FY2020. During the same period, demonstrated in Figure 1 (right), the RDT&E budget rose by 37.3%, making it the budget element with the greatest percentage increase and reflecting the DoD's focus on addressing emerging threats.

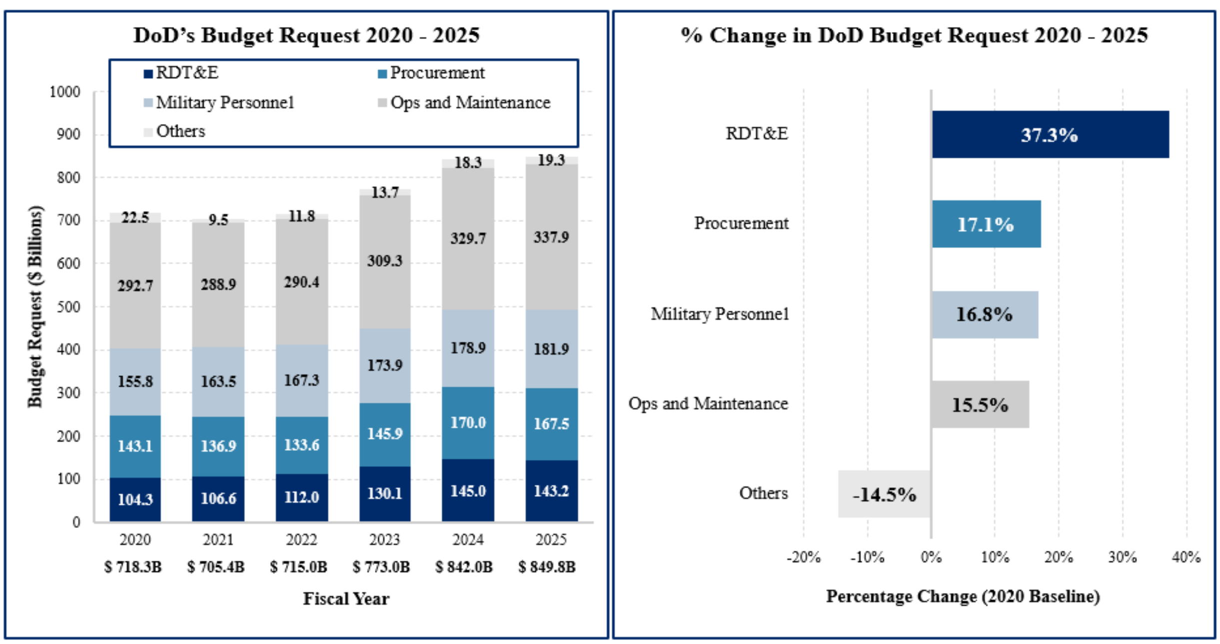

Figure 1. Budget Request (left) and Percentage Changes (right) between 2020 and 2025

Although the DoD shares general budgetary information, specific details about its programs remain confidential. This confidentiality makes it more difficult for industry stakeholders to identify key challenges and align their efforts with defense needs.

Cyber-Physical Systems (CPS) and Unmanned Aerial Vehicles (UAVs)

Cyber-Physical Systems combine computing, communication, and physical processes to monitor and control real-world environments[9], as represented in Figure 2. In this context, CPS may face different challenges such as dependability, maintainability, availability, safety, reliability, robustness, predictability, reconfigurability, security, confidentiality, heterogeneity, and scalability[10]. This paper identifies the ones of greatest concern to the DoD.

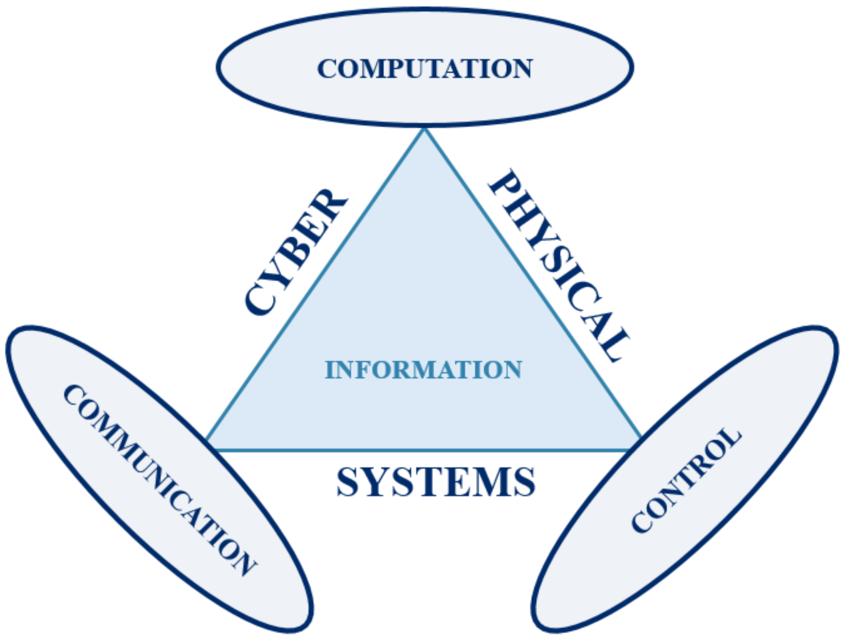

Figure 2. The 3Cs of Cyber-Physical Systems

Unmanned Aerial Vehicles, also known as drones, are aircraft that operate without a pilot onboard. UAVs rely on systems, often powered by CPS, to navigate complex environments and perform their missions with efficiency.

Department of Defense (DoD) Cyber-Physical Strategy

The Department of Defense protects national security and addresses various threats, including those posed by advanced technologies. Each year, the DoD submits a budget request to Congress to support its strategic objectives. DoD operates over 11,000 Unmanned Aircraft Systems (UAS)[11], which have become essential to military operations. According to the Federal Aviation Administration (FAA), a UAS consists of the UAV, CPS, and associated equipments[12].

The DoD's Cyber Strategy[13] outlines four primary goals: protecting the cyber domain, defending the nation, preparing for future conflicts, and developing technological advantages. This research aligns the identified CPS challenges with the DoD's goals and shows which challenges should be prioritized by the defense industry.

Kern Entrepreneurial Engineering Network (KEEN)

KEEN is transforming engineering education by combining theoretical learning with practical applications. It emphasizes three key principles: connections, curiosity, and creating value[14]. These principles enable engineers to develop critical skills such as innovative design, opportunity recognition, and understanding the broader impact of their work.

Curiosity has long been recognized as a fundamental driver of innovation and discovery. It can be categorized into two distinct dimensions: epistemic curiosity and diverse curiosity. Epistemic curiosity[15] refers to the desire for knowledge and understanding, driven by the need to resolve uncertainty. In this research, epistemic curiosity aligns with the understanding of DoD strategies aimed at enhancing the capabilities of Cyber-Physical Systems in UAVs.

Diverse curiosity[16] fosters creativity by exploring possibilities. It is reflected in this paper by identifying key challenges for the defense industry to prioritize. Given the constraints of time and resources, it is impossible to address all challenges simultaneously. Thus, diverse curiosity helps guide industry efforts to solve the most pressing issues first.

KEEN fosters a mindset that interlinks engineering education and solution of actual problems. Epistemic curiosity is enhanced so that students of engineering are able to systematically explore CPS security and reliability issues, making learning adaptive to industry needs. Variety of curiosity then fosters adaptability for students to conceptualize future trends in UAV systems. Incorporating such a mindset in engineering curricula can potentially empower students to solve challenging aerospace and defense problems.

Problem Statement

The Department of Defense depends on Cyber-Physical Systems and UAVs for critical defense operations. With adversaries advancing technologically and operational environments becoming more complex, it is necessary to evaluate whether these systems effectively address emerging threats. Despite increased investments in Research, Development, Testing, and Evaluation, a more comprehensive understanding of the specific challenges remains unclear. Identifying them is essential to ensure that industry can support the DoD and support national defense goals.

Research Questions (RQs)

RQ1: CPS in UAV: What are the challenges being addressed by DoD?

RQ2: Industry Focus: Which challenges should be the top priority to address?

Contribution

This paper explores the current state of CPS and UAV technologies in the DoD, focusing on identifying challenges and operational gaps. It addresses these issues using a curiosity-driven approach inspired by KEEN. The findings are expected to help guide future industry strategies when developing modern technologies.

Methodology

Materials

The analysis utilized Excel for detailed calculations involving U.S. Department of Defense data, with a specific focus on program costs and their alignment with identified challenges. PowerPoint was employed to create visualizations, including graphs and charts, to effectively communicate the findings.

KEEN mindset played a significant role in shaping the study's curiosity-driven approach. Epistemic curiosity guided the investigation of the DoD Budget Overview and RDT&E Programs (R1)[17], enabling a better understanding of CPS challenges being addressed by DoD. Meanwhile, diverse curiosity was leveraged to explore innovative prioritization strategies for the defense industry, ensuring alignment with the DoD Cyber Strategy Summary.

DoD Budget Request Analysis and Challenges Identification

To identify the challenges, Budget Activities (BAs) from the RDT&E appropriations related to CPS and UAVs were first selected. Once identified, all Program Elements within these BAs were individually analyzed and recorded in Excel. Program Elements specifically associated with CPS and UAVs were then selected for detailed analysis. The total budget allocated to each Program Element was obtained from the RDT&E Programs (R1)[17].

While the documents reviewed did not explicitly mention the challenges, the existence of these issues became evident through a deeper analysis using a curiosity-driven mindset. Using KEEN's principles, this study systematically explored publicly available DoD documents to identify underlying patterns and establish relationships between resource allocation and potential threats.

To estimate the allocation of DoD resources for addressing gaps in CPS and UAVs, three primary calculations were performed: Average Cost per Challenge (1), Total Cost by Challenge (2), and Percentage Distribution per Challenge (3).

$$Average\ Cost\ per\ Challenge = \frac{Total\ Budget\ allocated\ to\ the\ Program\ Element}{Number\ of\ Challenges\ Adressed} \quad (1)$$

$$Total\ Cost\ per\ Challenge = \sum_{i=1}^{n} Average\ Cost\ per\ Challenge\ in\ Program\ Element\ i \quad (2)$$

$$\%\ Distribution\ per\ Challenge = \frac{Total\ Cost\ per\ Challenge}{Total\ Budget\ of\ all\ Program\ Elements}\ x\ 100\% \quad (3)$$

Results

Budget Activities and Allocations

Among the eight Budget Activities within the DoD's RDT&E, five were linked to Cyber-Physical Systems and UAVs: Operational Systems Development, Advanced Component Development & Prototypes, System Development & Demonstration, Advanced Technology Development, and Applied Research, as illustrated in Figure 3. The analysis of these BAs revealed substantial investments in CPS and UAV capabilities.

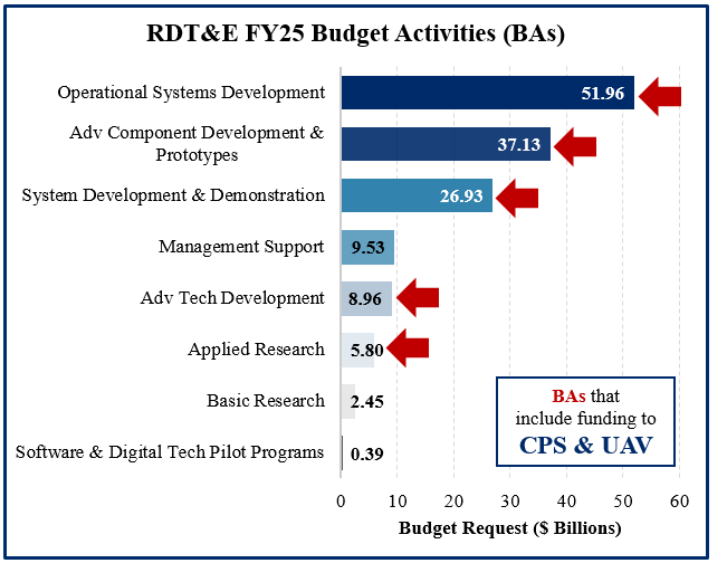

Figure 3. Budget Activities in DoD's Research, Development, Training, and Evaluation

Program Elements and Distribution across Military Branches

The program elements within the selected BAs were analyzed to identify those specifically related to Cyber-Physical Systems and Unmanned Aerial Vehicles. Of the 959 total program elements, 121 were identified as related to CPS and UAV technologies, as shown in Figure 4. This corresponds to approximately $8.95B requested by DoD to use in RDT&E. These findings highlight the strategic importance of CPS and UAV advancements in strengthening the capabilities of all branches of the military.

MILITARY BRANCHES	TOTAL PROGRAMS	TOTAL BUDGET	TOTAL PROG. CPS/UAV	TOTAL CPS/UAV BUDGET
ARMY	206	$ 14,073,308,000	30	$ 2,265,065,000
NAVY	233	$ 25,697,815,000	45	$ 2,827,719,000
AIRFORCE	232	$ 49,108,771,000	19	$ 1,087,957,000
SPACE FORCE	57	$ 18,700,153,000	7	$ 1,038,238,000
DEFENSE WIDE	231	$ 35,227,834,000	20	$ 1,731,485,000
TOTAL	**959**	**$ 142,807,881,000**	**121**	**$ 8,950,464,000**

Figure 4. Total CPS and UAV Programs with allocated budgets based on military branches.

Cost Analysis, Challenges Identification, and their Percentage Distribution

RQ1: CPS in UAV: What are the challenges being addressed by DoD?

Budget allocations related to CPS and UAV technologies were identified and analyzed within the selected program elements. Among the CPS known common issues[10], after analyzing each of the Program Elements, it was possible to identify six key challenges such as Dependability, Reliability, Predictability, Sustainability, Security, and Interoperability. Using the average cost per challenge, resource allocation for each issue was estimated. Figure 5 presents the findings for the Top 10 Program Elements based on budget allocation[17].

Item	Budget Allocation FY 2025 ($ Millions)	Dependability ($ Millions)	Reliability ($ Millions)	Predictability ($ Millions)	Sustainability ($ Millions)	Security ($ Millions)	Interoperability ($ Millions)
Future Long Range Assault Aircraft Development	$ 1,253.64	$ 208.94	$ 208.94	$ 208.94	$ 208.94	$ 208.94	$ 208.94
Space Situation Awareness Systems	$ 483.61	$ 80.60	$ 80.60	$ 80.60	$ 80.60	$ 80.60	$ 80.60
Advanced Nuclear Power Systems	$ 368.00	$ 73.60	$ 73.60		$ 73.60	$ 73.60	$ 73.60
Acq Workforce - Nuclear Systems	$ 343.18		$ 114.39		$ 114.39		$ 114.39
Command, Control and Communications Systems	$ 336.54		$ 84.14		$ 84.14	$ 84.14	$ 84.14
ACQ Workforce - Space & Missile Systems	$ 274.42	$ 54.88		$ 54.88	$ 54.88	$ 54.88	$ 54.88
Advanced Aerospace Systems	$ 269.70		$ 89.90			$ 89.90	$ 89.90
Aviation Systems	$ 263.71	$ 43.95	$ 43.95	$ 43.95	$ 43.95	$ 43.95	$ 43.95
Warrior Systems	$ 245.88	$ 40.98	$ -	$ -	$ -	$ -	$ -
Unmanned Carrier Aviation (UCA)	$ 214.92	$ 53.73		$ 53.73	$ 53.73	$ 53.73	

Figure 5. Top 10 Program Elements based on DoD's requested budget.

The total cost for each challenge was then aggregated across all program elements. Security, Dependability, and Sustainability emerged as the most significant areas of investment, reflecting their critical importance in advancing CPS and UAV systems. To gain deeper insights into resource prioritization, the percentage distribution of the total budget across challenges was calculated, offering a clearer picture of how the DoD allocates resources to address these pressing issues.

Alignment with DoD Cyber Strategy Goals

RQ2: Industry Focus: Which challenges should be the top priority to address?

The identified challenges and their corresponding budget allocations were mapped to the goals outlined in the DoD Cyber Strategy, as illustrated in Figure 6. This alignment demonstrates how investments in CPS and UAV technologies advance strategic objectives, including protecting the cyber domain, defending the nation, preparing to fight and win, and developing a cyber advantage. The defense industry should prioritize addressing the challenges with the highest budget allocations, as these are likely to represent the most pressing national defense concerns.

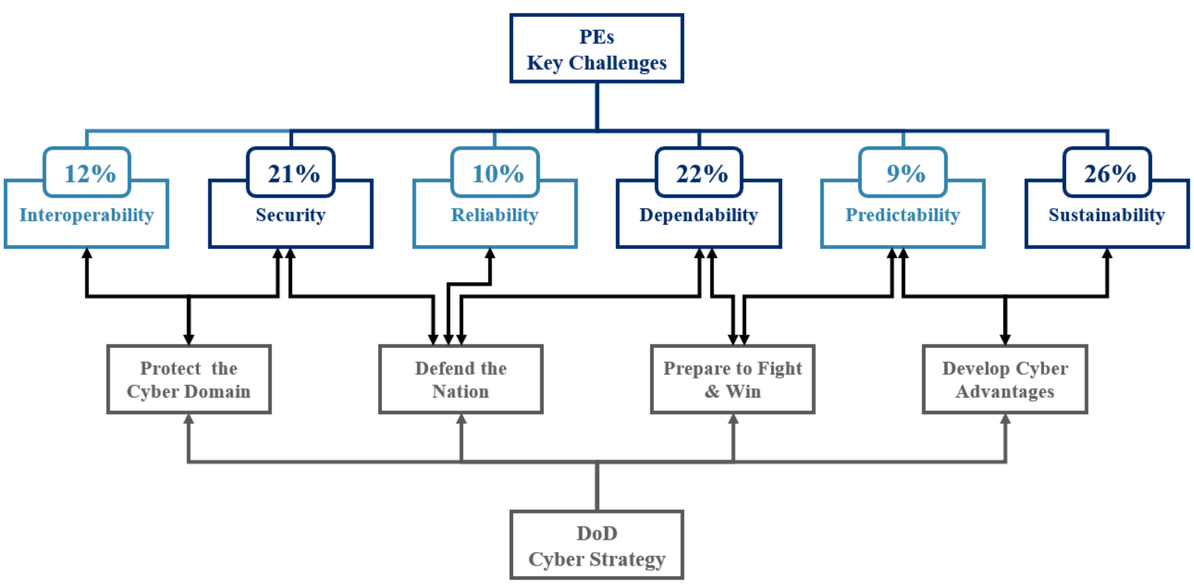

Figure 6. CPS and UAV challenges and how they associate to DoD's Cyber Strategy

Discussion

Interpretation of Results

RQ1: CPS in UAV: What are the challenges being addressed by DoD?

The result of this study identifies the primary concerns faced by DoD with Cyber-Physical Systems and Unmanned Aerial Vehicles: Interoperability, Security, Reliability, Dependability, Predictability, and Sustainability.

Interoperability ensures that systems and components function together, enabling communication and coordination across platforms in complex operational environments. Security is fundamental for protecting systems against cyber threats and keeping data confidentiality, integrity, and availability. Reliability focuses on consistent system performance under expected conditions, while Dependability emphasizes minimizing disruptions and maintaining operational continuity. Predictability ensures system behaviors can be anticipated with confidence. Sustainability prioritizes long-term viability, resource efficiency, and environmental impact reduction[10].

The conclusions of this study offer insights not only to the defense community but also to engineering education. The challenges realized are prime fields in CPS and UAV technology development. Engineering schools can conclude from these results the need for incorporating cybersecurity fundamentals, reliability engineering, and design for sustainability in their curricula. By involving project-based instruction with hands-on applications that are reflections of true DoD issues, students will be better able to prepare for careers in aerospace and defense

RQ2: Industry Focus: Which challenges should be the top priority to address?

Among these, Security, Dependability, and Sustainability emerged as the most critical challenges, being associated with 69% of the budget allocation to CPS and UAV technologies. These three areas not only address critical operational needs but also align directly with all DoD Cyber Strategy goals, showing where the defense industry should focus their efforts when working in CPS and UAV.

The KEEN framework played an essential role in this research. Epistemic curiosity drove the in-depth analysis of DoD's resource allocation, revealing underlying patterns and systemic relationships critical to identifying challenges while diverse curiosity informed the strategic prioritization of industry efforts.

Implications in the Defense Industry

This study’s findings are relevant to the defense industry, offering a clear roadmap for prioritizing investments and aligning technological developments with the strategic objectives of the Department of Defense. By identifying key challenges and their alignment with DoD Cyber Strategy goals, the research highlights critical areas where industry stakeholders can focus efforts to meet emerging operational demands and maintain technological superiority.

Limitations of the study
This study was constrained by limited access to detailed and classified data due to the sensitive nature of military products.

Suggestions for future work
Future research should focus on understanding the specific CPS technologies currently integrated into UAVs used by the DoD. A comprehensive evaluation of contractor products and their alignment with DoD strategic objectives would provide valuable insights for improving future procurement and development efforts.

Conclusion

The six key challenges identified are Interoperability, Security, Reliability, Dependability, Predictability, and Sustainability (***RQ1***). Among these, Security, Dependability, and Sustainability emerged as the most critical (***RQ2***). These challenges highlight areas where the defense industry should concentrate its efforts in developing CPS and UAVs.

This study also highlights the importance of using KEEN curiosity-driven approach to map these challenges to the goals outlined in the DoD Cyber Strategy. This alignment ensures that industry investments are directed toward areas that directly enhance operational capabilities and address national security priorities.

In addition to its relevance to the defense industry, this study highlights the importance of engineering education in producing the aerospace leaders of tomorrow. By incorporating CPS challenges into capstone projects, industry collaborations, and research projects, universities can equip students with the know-how necessary to confront emerging threats in UAV technology. Improving these education platforms will ensure that the engineers of tomorrow are well-positioned to enhance national security and technology.

Disclaimer Statement
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