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Scientific and Technological Advancement in Outer Space: Emerging Legal Challenges of Resource Exploitation

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ABSTRACT

The rapid transformation of outer space from a domain dominated by governmental exploration into a commercially active environment has created a new relationship between scientific advancement, resource exploitation, environmental protection, and international law. Advances in launch systems, satellite constellations, autonomous robotics, artificial intelligence, remote sensing, in-space manufacturing, lunar exploration, and in-situ resource utilization have significantly expanded the capacity of States and private entities to use extraterrestrial environments. At the same time, these developments have generated environmental consequences that were largely absent from the early architecture of international space law. Orbital congestion, space debris, atmospheric effects of launches and re-entries, contamination of celestial bodies, disturbance of lunar and planetary environments, and the prospective extraction of water, minerals and other resources raise questions about the environmental limits of scientific and commercial activity beyond Earth. The problem is particularly significant because outer space is simultaneously an operational environment, a scientific domain, a potential resource frontier and an area recognized as the province of all humankind. The international legal framework, principally the 1967 Outer Space Treaty, the Liability Convention, the Registration Convention and subsequent United Nations principles, provides important foundations but was developed before the emergence of mega-constellations, private space-resource enterprises and large-scale commercial lunar activity. This article examines the environmental implications of scientific and technological advancement in outer space and evaluates whether existing international law is capable of responding to the transition from exploration to exploitation. It argues that space environmental protection should no longer be treated merely as an aspect of operational safety. Instead, it should become a central principle of international space governance. Drawing upon scientific data available through 2024, the article demonstrates the scale of orbital environmental degradation and examines the need for precaution, intergenerational equity, planetary protection, environmental impact assessment, debris mitigation, responsible resource utilization and stronger international cooperation. It proposes an integrated model of space environmental governance capable of reconciling scientific progress with the long-term preservation of outer space for future generations.

Keywords: *outer space, space environment, space debris, resource exploitation, international space law, planetary protection.*

1. Introduction

The history of space activity has entered a fundamentally different phase. The first decades of the Space Age were principally characterized by scientific exploration, military competition and government-led programmes. Contemporary space activity, by contrast, is increasingly shaped by commercial launch providers, private satellite operators, large communications constellations, robotic exploration, lunar missions, space tourism and emerging plans for the extraction and utilization of extraterrestrial resources. Scientific and technological progress has consequently changed not only what humanity can do in outer space but also the environmental consequences of doing it. The transformation is visible most clearly in low-Earth orbit, where the number of operational satellites and fragments has increased dramatically. The European Space Agency reported in its 2024 Space Environment Report that approximately 35,000 objects were being regularly tracked by space surveillance networks, including about 9,100 active payloads and approximately 26,000 pieces of debris larger than 10 centimeters. More significantly, modelling indicated that the number of debris objects larger than one centimeter exceeded one million, illustrating that the environmental problem cannot be understood merely through objects large enough to be routinely tracked (European Space Agency [ESA], 2024). The United Nations also recorded that 212 successful launches and deployments associated with the International Space Station in 2023 resulted in approximately 2,900 new satellites being placed in Earth orbit or beyond, while 377 rocket bodies and debris objects were added to the orbital population (United Nations Office for Outer Space Affairs [UNOOSA], 2024). These figures illustrate a fundamental paradox. Scientific advancement makes space-based services increasingly indispensable for communication, navigation, weather forecasting, disaster management, agriculture, climate observation and scientific research, yet the technological infrastructure producing these benefits can simultaneously degrade the environment upon which future space activities depend. The environmental dimension becomes even more complex when the discussion moves beyond Earth orbit. The Moon, asteroids and other celestial bodies are increasingly being considered as potential sources of water, minerals, metals and other materials. In-situ resource utilization could eventually reduce the enormous costs of transporting materials from Earth and facilitate sustained human presence beyond Earth. Water ice on the Moon, for example, may be converted into drinking water, oxygen and hydrogen propellant, potentially making lunar infrastructure more economically viable. Asteroid resources could similarly become technologically accessible as robotics, autonomous navigation and space manufacturing develop. The scientific rationale for such activities is therefore substantial. However, resource utilization also raises an environmental question: whether humanity should apply terrestrial concepts of extraction to environments that possess limited or no capacity for ecological recovery. The concept of environmental sustainability must consequently be extended beyond Earth. Recent scholarship argues that space sustainability requires consideration of the physical environment of orbital and celestial domains rather than merely the continuity of commercial operations (Mo et al., 2024). The legal significance of this development is equally profound. Article I of the Outer Space Treaty establishes that the exploration and use of outer space shall be carried out for the benefit and in the interests of all countries, while Article II prohibits national appropriation of outer space, including the Moon and other celestial bodies. Article VI establishes international responsibility for national activities in outer space and requires States to authorize and continuously supervise the activities of non-governmental entities. Article IX requires States to conduct activities with due regard to the corresponding interests of other States and to avoid harmful contamination of celestial bodies and adverse changes in the environment of Earth resulting from the introduction of extraterrestrial matter. These provisions constitute the foundation of contemporary space environmental law. Yet they were formulated in 1967, at a time when the number of satellites was comparatively small and commercial exploitation of lunar or asteroid resources remained largely speculative. The challenge today is therefore not simply whether existing space law remains relevant, but whether its broad principles can be translated into operational environmental standards appropriate for a technologically sophisticated and commercially expanding space sector. The central argument of this article is that scientific advancement and resource exploitation should not be treated as alternatives to environmental protection. Rather, scientific progress requires a legal framework capable of ensuring that the benefits of space technology are not secured at the expense of the long-term usability and scientific integrity of outer space.

2. Scientific and Technological Transformation of Outer Space

The environmental challenges of contemporary space activity cannot be understood without recognizing the scale and speed of technological transformation. Advances in launch vehicles, miniaturized satellites, reusable launch systems, electric propulsion, autonomous spacecraft, artificial intelligence, robotics and high-throughput communications have substantially reduced the economic and technical barriers to space operations. Small satellites and constellation-based architectures have allowed private companies and emerging space nations to participate in activities once dominated by a limited number of major space powers. Large constellations are particularly significant because they change the physical characteristics of the orbital environment. ESA reported that more than 6,000 active satellites were located between approximately 500 and 600 kilometres altitude in 2024, with this orbital region becoming increasingly concentrated because of the deployment of communication constellations (ESA, 2024). The growth of such systems has produced considerable social benefits, including broadband connectivity, remote sensing and improved access to information, but it has also intensified collision risks and increased demands upon space traffic coordination. Orbital space is therefore increasingly comparable to a congested environmental commons in which the activities of one operator can impose risks and costs upon others. The scientific problem is not restricted to collisions. A satellite that becomes non-functional, a spent upper stage left in orbit, a fragmentation event or an intentional destruction of a spacecraft can produce thousands of fragments travelling at extremely high velocities. At orbital speeds, even small fragments can possess sufficient kinetic energy to damage or destroy operational spacecraft. The possibility of cascading collisions, often associated with the concept of the Kessler syndrome, demonstrates how environmental degradation can become self-reinforcing. ESA's assessment has repeatedly emphasized that a collision or explosion capable of producing large numbers of fragments could make heavily utilized orbital regions increasingly hazardous for both existing satellites and future spacecraft (ESA, 2024). Scientific advancement also creates environmental consequences during launch and re-entry. Rocket combustion releases gases and particles into the atmosphere, while the increasing frequency of launches introduces an emerging atmospheric dimension to space sustainability. Although the scale and long-term effects of launch emissions remain subjects of scientific research, the rapid expansion of launch activity means that atmospheric impacts should not be ignored simply because the activity occurs primarily in support of space missions. Re-entry creates another environmental interface between space and Earth because spacecraft and rocket stages may burn up in the atmosphere, depositing material and potentially creating risks for ecosystems and human populations. India provides a useful illustration of the changing operational environment. The Indian Space Research Organisation's Indian Space Situational Assessment Report 2024 recorded 254 launches and on-orbit breakup events contributing 3,665 objects to the space-object population during the year. It also recorded 2,095 catalogued re-entries, the highest number reported in that assessment, including 335 Starlink satellites deliberately deorbited as part of a large-scale disposal programme (Indian Space Research Organization [ISRO], 2025). These data demonstrate that environmental management is becoming inseparable from routine space operations. At the same time, technological development is extending beyond Earth orbit. Robotic landers, rovers and autonomous systems are enabling increasingly sophisticated lunar and planetary missions. The emerging concept of in-space servicing, assembly and manufacturing may eventually permit spacecraft to be repaired, refueled or constructed in orbit rather than launched fully assembled from Earth. Such capabilities could reduce launch requirements and potentially improve the efficiency of space infrastructure. Nevertheless, they also introduce new forms of environmental intervention. Manufacturing in orbit may create additional material residues; servicing activities may generate fragments; and permanent infrastructure may alter the physical and scientific character of celestial bodies. The expansion of artificial intelligence adds another layer of complexity because autonomous spacecraft may make operational decisions without real-time human intervention. This can improve collision avoidance and resource efficiency but simultaneously creates questions concerning responsibility when autonomous systems produce environmental harm. Scientific advancement, therefore, should not be measured exclusively by technological capability. A mature concept of progress must also consider environmental consequences, reversibility, cumulative effects and the capacity of future generations to continue using the space environment.

3. Space Debris and the Environmentalisation of Orbital Space

Space debris represents the clearest example of the need to reconceptualise outer space as an environmental domain. Unlike terrestrial pollution, orbital pollution cannot simply be removed through conventional waste-management systems. Objects travel at orbital velocity, occupy different trajectories and may remain in orbit for years or decades. Consequently, prevention is generally more effective than post-incident remediation. ESA's 2024 data indicated approximately 35,000 regularly tracked objects, with more than one million objects larger than one centimetre estimated to exist in Earth's orbital environment (ESA, 2024). The significance of these figures is not merely numerical. They reveal a transition from a relatively open operational environment to a crowded physical system in which the cumulative consequences of past activities constrain present and future missions. The problem is particularly severe in low-Earth orbit because of the large number of satellites and the concentration of objects within certain altitude bands. ESA reported that approximately two-thirds of active satellites were located between 500 and 600 kilometres altitude in 2024, producing significant congestion in these regions (ESA, 2024). The environmental analogy is compelling. Atmospheric pollution, ocean pollution and orbital debris all involve the accumulation of human-generated material in shared environments where individual actors may receive private benefits while imposing diffuse costs on others. The legal problem is consequently one of externalities and collective action. A satellite operator can benefit from a constellation while part of the cost of maintaining a safe orbital environment is distributed among every other operator. International law attempts to address this problem through the Outer Space Treaty, the Liability Convention and United Nations guidelines, but the system remains heavily dependent upon national implementation. Article VI of the Outer Space Treaty requires States to authorize and continuously supervise non-governmental activities, making national licensing systems a critical mechanism for environmental protection. Article IX's requirement of due regard and avoidance of harmful contamination provides a broad legal basis for environmental responsibility. However, these obligations do not establish detailed numerical standards for collision probability, post-mission disposal, satellite design, active debris removal or maximum orbital occupancy. The United Nations Guidelines for the Long-term Sustainability of Outer Space Activities, adopted by COPUOS in 2019, represent an important development because they contain 21 guidelines addressing policy, regulatory, operational, scientific, technical and international cooperation issues (Martinez, 2021). Yet their principal weakness is their voluntary and non-binding character. Their value lies in establishing an internationally accepted baseline of responsible behavior rather than creating a comprehensive enforcement regime. The environmental significance of these guidelines is nevertheless substantial because they encourage States to incorporate sustainability throughout the mission life cycle. The question for the next stage of space governance is whether these principles should gradually evolve into binding standards. One possible approach would be mandatory post-mission disposal requirements, particularly for satellites operating in heavily congested orbital regions. Another would be compulsory collision-avoidance capabilities, conjunction-data sharing and registration of spacecraft manoeuvres. Active debris removal presents a more complicated problem because removing abandoned objects can itself create legal and security concerns. A spacecraft approaching another State's defunct satellite may be interpreted as a potentially hostile act, even when its stated purpose is environmental remediation. This illustrates why environmental governance cannot be separated from security governance. The legal framework should therefore distinguish clearly between responsible remediation and activities that could threaten the security of other space actors. Environmental liability also requires reconsideration. Existing international liability rules largely depend on concepts of fault and damage that were developed for a much smaller space sector. As the number of operator increases, proving causation in a chain collision becomes increasingly difficult. The environmental principle of prevention therefore deserves greater weight than after-the-fact liability. A responsible space regime should make environmentally sustainable mission design a condition of market access rather than relying principally upon litigation after damage occurs.

4. Lunar and Planetary Resource Exploitation: Environmental Risks beyond Earth

The next major environmental challenge arises from the movement from orbital utilization toward extraction of extraterrestrial resources. The Moon is central to this transformation because it is relatively accessible and may contain water ice and other scientifically and economically valuable materials. The development of in-situ resource utilization technologies could enable future missions to extract and process local materials for life support, construction and propulsion. This could reduce dependence upon Earth-based supply chains and make sustained exploration more feasible. From an environmental perspective, however, the Moon should not be regarded as an empty territory simply because it lacks an Earth-like biosphere. Lunar environments contain scientifically significant geological records, volatile deposits and locations of exceptional scientific interest. The physical disturbance caused by landing systems, excavation, drilling, construction and repeated vehicle movement may permanently alter surface features. The absence of conventional ecosystems does not eliminate environmental value. Scientific environments themselves constitute resources for future generations because lunar geology preserves information about the history of the Earth-Moon system and the Solar System. The emerging concept of space environmental sustainability therefore requires a broader definition of environmental harm. Recent research argues that sustainability in planetary exploration should include protection of lunar and Martian environments from forms of disturbance extending beyond biological contamination (Mo et al., 2024). The legal foundation for this approach can be found partly in Article IX of the Outer Space Treaty, which requires States to avoid harmful contamination of celestial bodies and adverse changes in the environment of Earth resulting from the introduction of extraterrestrial matter. The provision, however, was drafted largely with scientific contamination and environmental protection in mind rather than large-scale mining. It does not specify how much physical alteration constitutes unacceptable environmental damage. Nor does the Outer Space Treaty explicitly establish a comprehensive system for environmental impact assessment before resource extraction. This regulatory uncertainty is particularly important because national approaches to space-resource activities have developed rapidly. The United States enacted the Commercial Space Launch Competitiveness Act in 2015, and Luxembourg and other States subsequently established domestic legal frameworks concerning space resources. The Artemis Accords also address the extraction and utilization of space resources and establish principles concerning the peaceful use of resources and the creation of temporary safety zones. These developments demonstrate the emergence of a practical regulatory architecture outside a new multilateral treaty. Nevertheless, the environmental dimension remains insufficiently developed. The principal question is not merely whether resource extraction is legally permissible, but under what environmental conditions it should occur. A scientifically credible system should require baseline environmental surveys before extraction, monitoring during operations and post-operation assessment. Activities involving lunar Polar Regions should receive particular scrutiny because permanently shadowed regions may contain scientifically important volatile deposits. The principle of precaution is therefore highly relevant. Where scientific knowledge concerning an extraterrestrial environment is incomplete, the absence of demonstrated ecological harm should not automatically be treated as evidence that no harm exists. Environmental assessment should instead precede large-scale intervention. Planetary protection also becomes more complicated as human missions expand. The Committee on Space Research has developed planetary-protection principles aimed at preventing biological contamination between Earth and other celestial bodies. Yet future commercial exploitation may involve much larger physical interventions than earlier scientific missions. The legal system will consequently need to address not only biological contamination but also geological disturbance, chemical contamination, dust mobilization, alteration of volatile deposits, interference with scientific sites and cumulative impacts arising from multiple operators. The concept of environmental carrying capacity may therefore become relevant to lunar governance. Certain regions may require strict protection, others controlled scientific access, and still others regulated resource utilization. Such differentiation would allow scientific and commercial development without treating every part of the lunar environment as equally available for exploitation.

5. International Space Law and the Limits of the Existing Regulatory Framework

International space law provides a foundational structure for regulating environmental consequences, but its capacity to address twenty-first-century exploitation is limited by technological and institutional gaps. The Outer Space Treaty remains the central legal instrument. Its principles of non-appropriation, peaceful exploration, international responsibility, due regard and avoidance of harmful contamination provide a normative framework capable of supporting environmental governance. The Rescue Agreement, Liability Convention and Registration Convention supplement this framework, while the Moon Agreement contains more detailed provisions concerning lunar resources and the Moon as the common heritage of humankind. However, the Moon Agreement has not achieved broad participation among the major spacefaring powers and therefore has limited practical influence over the emerging commercial resource sector. The central weakness of the broader system is the absence of a comprehensive environmental regime comparable to those developed for oceans, international waters or other global commons. The international environmental law principles of prevention, precaution, environmental impact assessment, intergenerational equity, sustainable development and polluter responsibility have developed substantially since 1967, yet their integration into space law remains incomplete. The United Nations Guidelines for the Long-term Sustainability of Outer Space Activities are significant precisely because they represent an attempt to translate contemporary sustainability principles into the space context. The guidelines recognize that the orbital environment is finite and that increasing numbers of governmental and non-governmental actors require international cooperation (Martinez, 2021). The United Nations describes long-term sustainability as the ability to conduct space activities indefinitely while preserving the outer space environment for future generations and ensuring equitable access to the benefits of peaceful exploration and use (UNOOSA, n.d.). Nevertheless, the voluntary character of the guidelines creates an implementation gap. States remain the principal gatekeepers because Article VI of the Outer Space Treaty makes them internationally responsible for national activities, including those of private entities. National licensing therefore becomes the immediate instrument through which environmental principles can be converted into enforceable requirements. States could require operators to demonstrate debris-mitigation compliance, collision-avoidance capacity, end-of-life disposal, and environmental monitoring and emergency-response capability before receiving licenses. They could also establish financial mechanisms under which operators contribute to the cost of orbital remediation. Such a system would internalize environmental externalities and create economic incentives for responsible design. International coordination is equally necessary. Orbital objects do not respect national borders, and debris generated by one operator may threaten spacecraft belonging to another State. A purely national approach therefore cannot adequately protect the shared environment. Space traffic coordination, data sharing and common technical standards should be developed through multilateral institutions. The same principle applies to lunar and asteroid resource exploitation. A fragmented national licensing system could encourage regulatory competition in which companies select jurisdictions offering the lowest environmental standards. International minimum standards would reduce this risk. The development of an international environmental impact assessment framework for major space activities would be particularly valuable. Such an assessment should consider the entire mission life cycle, including launch, operation, disposal or re-entry and, where relevant, resource extraction and site restoration. The assessment should also consider cumulative effects rather than evaluating each mission in isolation. This is essential because the environmental significance of a single satellite may be relatively small while thousands of satellites collectively transform the orbital environment. Scientific expertise must therefore be incorporated into legal decision-making. Environmental regulation should be based on measurable indicators such as collision probability, orbital lifetime, debris-generation potential, environmental disturbance, and contamination risk and resource depletion. In this respect, law should not attempt to replace science; it should establish institutions capable of translating scientific knowledge into enforceable standards.

6. Toward an International Regime of Space Environmental Governance

The future of space activity requires a transition from a predominantly safety-oriented model toward a comprehensive environmental governance model. The distinction is important. Safety regulation generally seeks to prevent immediate harm to spacecraft, astronauts and infrastructure, whereas environmental regulation addresses cumulative, long-term and intergenerational effects. Outer space increasingly requires the latter approach. The 2024 scientific literature on space environmental sustainability emphasizes that conventional sustainability concepts developed for terrestrial environments are insufficient for increasingly complex in-space manufacturing and exploration activities (Mo et al., 2024). A future international regime should begin with recognition of outer space as a shared environmental domain whose long-term utility is a collective interest. This does not require treating outer space as identical to Earth's natural ecosystems. Rather, it requires acknowledging that orbital regions and celestial environments possess finite physical characteristics and that irreversible alteration may affect future scientific and economic opportunities. First, the principle of prevention should become the foundation of space environmental regulation. Operators should be required to design spacecraft and missions to minimize debris production, avoid unnecessary orbital lifetime and maximize safe disposal. Second, environmental impact assessment should become standard for activities capable of producing significant environmental effects. This should include major constellations, large orbital infrastructure, active debris-removal missions, lunar mining and permanent installations on celestial bodies. Third, the precautionary principle should guide activities where scientific knowledge is incomplete. The absence of evidence of harm should not automatically justify irreversible intervention. Fourth, the polluter-pays principle could be adapted to space operations. Operators whose activities create disproportionate environmental risks should bear a greater share of the cost of remediation and monitoring. An international orbital environmental fund could support debris-removal projects and technical assistance for developing space nations.

Fifth, space-resource activities should be governed through a sustainability-based licensing system. Licenses should require scientific baseline assessments, environmental monitoring, operational transparency and post-mission responsibilities. Sixth, protected scientific areas should be established around locations possessing exceptional geological, astronomical or historical value. Such protection would be particularly relevant to the lunar surface, where early landing sites, Polar Regions and unique geological formations may have importance extending beyond immediate commercial interests. Seventh, the international community should strengthen data-sharing mechanisms. Space environmental governance depends upon accurate knowledge of object trajectories, spacecraft status, debris populations and environmental conditions. The existing growth of commercial constellations makes shared situational awareness increasingly important. ESA's 2024 assessment shows why this is urgent: the orbital population continues to rise and collision-avoidance events are becoming increasingly necessary as congestion increases (ESA, 2024). The regulatory architecture should also account for equity. Developing countries should not be excluded from the benefits of space technology because orbital resources become dominated by early commercial actors. The UN sustainability framework explicitly links long-term sustainability with equitable access to the benefits of peaceful exploration and use (UNOOSA, n.d.). This principle should influence future resource governance. Finally, international law should recognize that sustainability is a continuing obligation rather than a one-time licensing requirement. Operators should report environmental performance throughout the mission cycle, and States should periodically reassess standards in response to scientific developments. Such an adaptive regulatory model would be more capable of responding to technologies that cannot yet be fully predicted. The goal should not be to prevent commercialization or scientific progress. On the contrary, predictable environmental standards could increase investor confidence by reducing regulatory uncertainty and preventing future conflicts over resource access. Sustainable governance can therefore become an enabling condition for long-term commercial development rather than an obstacle to it.

7. Conclusion

The transition from space exploration to resource utilization represents one of the most consequential developments in contemporary science and technology. Advances in launch systems, satellite constellations, autonomous robotics, artificial intelligence, in-space manufacturing and resource-utilization technologies are expanding the physical and economic boundaries of human activity. Yet these advances are accompanied by an environmental cost that is becoming increasingly measurable. By 2024, approximately 35,000 objects were being tracked in Earth orbit, while modelling indicated more than one million debris objects larger than one centimeter (ESA, 2024). India alone recorded 3,665 objects added to the space-object population through launches and breakup events during 2024, while 2,095 catalogued objects re-entered the atmosphere (ISRO, 2025). Such figures demonstrate that the environmental consequences of space activity are no longer theoretical. They are already affecting the safety, accessibility and scientific utility of orbital space. The emerging exploitation of lunar and potentially asteroid resources creates a second environmental frontier. The challenge there is different because the principal concern is not only debris but also the physical alteration of environments whose scientific value may extend far beyond present economic interests.

Existing international space law provides important principles, particularly through the Outer Space Treaty and the United Nations framework on long-term sustainability, but its environmental provisions remain general and its most detailed sustainability guidelines are voluntary. The central legal challenge is therefore to transform broad principles into measurable and enforceable environmental standards without suppressing legitimate scientific and commercial activity. A future regime should incorporate environmental impact assessment, precaution, prevention, life-cycle responsibility, debris mitigation, sustainable resource extraction, scientific-site protection, transparent monitoring and equitable access to the benefits of space activities. The law should also respond to the cumulative nature of environmental harm. A single satellite or lunar excavation may appear insignificant in isolation, but thousands of activities undertaken simultaneously can fundamentally change the environment. The appropriate regulatory unit is therefore not merely the individual mission but the cumulative condition of the space environment. Scientific knowledge must remain central to this process. Environmental regulation without reliable data would be ineffective, while scientific advancement without legal responsibility could produce irreversible consequences. The appropriate relationship is therefore one of science-informed governance in which scientific evidence determines environmental thresholds and international law establishes duties, responsibilities and institutional mechanisms. Outer space should not be conceived as an unlimited frontier awaiting exploitation. It is a finite and interconnected physical environment upon which scientific research, communications, navigation, climate observation and future exploration depend. The principle that should guide the next phase of the Space Age is consequently not exploitation without limits, but responsible utilization within scientifically informed environmental boundaries. If humanity wishes to maintain access to outer space for future generations, sustainability must become a condition of scientific and commercial advancement rather than an afterthought to it.

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