SPACE SUSTAINABILITY IN THE CONTEXT OF CONGESTED AND CONTESTED SPACE

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Executive Summary

The last decade has seen dramatic changes in the scope and scale of space operations. These changes are straining the effectiveness of traditional practices to maintain a safe and sustainable operating environment. The number of satellites has risen to an unprecedented level and the potential for conflicts in space has also grown as space becomes more contested. If unmanaged, the combination of congested and contested space has the potential to make operating in parts of Earth orbit very difficult.

There are several stressors on the orbital environment with both short- and long-term consequences which include:

- Increase in space activity, large constellations, mass-produced satellites
- Concentration of satellites for large constellations
- Larger number of satellite operators across more countries
- Increase in number of derelict objects and debris, such as rocket bodies

These stressors can amplify the effects of a conflict in space, making the consequences far more severe than the direct effects of the conflict alone.

The sudden addition of large amounts of small debris or many additional derelict objects from a conflict in space can rapidly compound any existing orbital debris problems, resulting in significant long-term challenges for space operations. To prevent this, several observations can be made and critical actions should be taken:

- Managing the orbital debris environment is an intrinsically international effort.
- It is critical for all spacefaring nations to strictly adhere to responsible debris mitigation practices.
- The execution of debris mitigation is more critical given the potential for space conflict.
- Considerations of debris management goals should include margin for managing the effects of conflicts.
- Development of anti-satellite systems should consider the effects on future space operations. Congested and contested space effects must be considered in combination to maintain acceptable operating conditions in space.

Introduction

The last decade has seen dramatic changes in the scope and scale of space operations. These changes are straining the effectiveness of traditional practices to maintain a safe and sustainable operating environment. With the advent of large commercial constellations of mass-produced satellites for Earth observation and internet service, the number of active satellites has risen at an unprecedented rate (see Figure 1).

Many of the new developments in space activity have the potential to significantly improve life on Earth and our ability to operate and conduct business in space. The development of small, useful satellites with standardized form factors—enabling them to easily ride as secondary payloads on many launch vehicles—has significantly increased access to space for a wide variety of nations and even academic institutions.[1] Many new types of missions have been or will soon be demonstrated, including satellite servicing, life extensions for satellites,[2,3] space manufacturing,[4] and the removal of dead satellites and rocket bodies from space.[5,6,7,8] But, if not properly managed, these developments can have a negative effect on the future ability to operate safely and sustainably in space. Although space sustainability can cover a variety of issues, from the debris environment to radio frequency spectrum usage to maintaining dark and quiet skies for astronomy,[9,10] this paper focuses on aspects of space sustainability related to congestion and orbital debris as well as their effects on space operations and ground safety.

Space is also becoming more contested, which has the potential to significantly complicate the problems of congestion. Potential adversaries are developing counterspace threats, including kinetic weapons, and are demonstrating a willingness to use them. In 2007, China tested a direct ascent (DA) anti-satellite (ASAT) weapon that blew up one of its own satellites,[11] creating thousands of pieces of debris, many of which remain in orbit today. As another example, Russia tested a DA-ASAT weapon in 2021 that also generated thousands of pieces of debris.[12] India's DA-ASAT test in 2019, although creating a relatively low amount of short-lived orbital debris, signaled that other countries may wish to test ASAT capabilities as a political demonstration.[13] The combination of these changes to space operations is resulting in

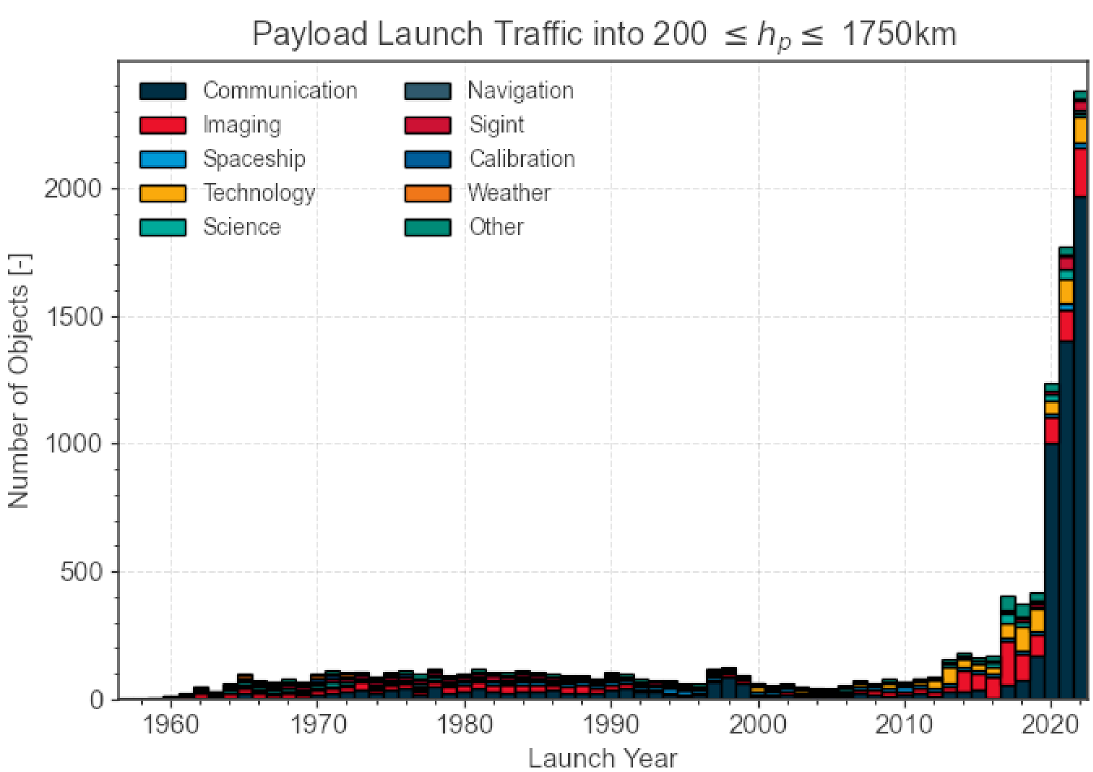


Figure 1: Evolution of launch traffic near LEO per mission type, from ESA 2023 Space Environment Report.

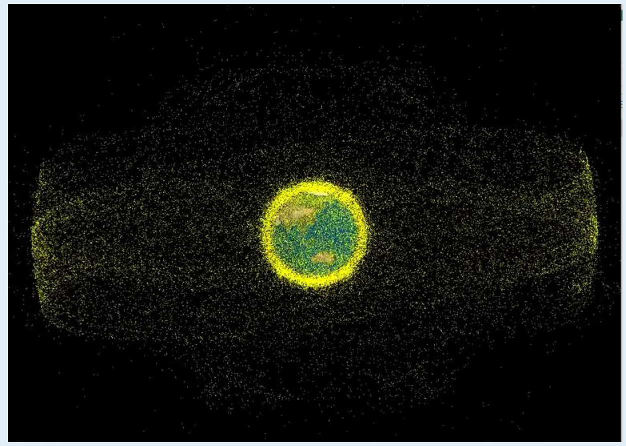
unprecedented stresses on maintaining a sustainable operating environment in space. U.S. government and commercial space leadership will need to carefully consider how to address these stressors to space sustainability, including how to manage them through policy and operations.

Space Traffic Consequences

The recent changes in space operations have the potential for negative effects on the space operational environment. The increase in space activity will mean more potential satellite failures and mass that could end up as debris. Large constellations of satellites in the same orbital regimes could lead to more collision risks. More operators managing satellites could result in coordination and communication challenges, and more launches could mean more derelict rocket bodies in orbit. In short, more traffic in space will increase the frequency of conjunctions and potential collisions between satellites and other objects; hence, operators will have to quickly respond and maneuver to avoid collisions and operate in an increasingly debris-filled environment.

Table 1 lists several of these environmental stressors and their short and their long-term negative effects.

Trackable Orbital Debris Environment



An important issue is the concept of "orbital capacity." Orbital capacity can have several different interpretations. It can encompass how many satellites can be operated within a certain region of space without producing numerous potential collisions, how many satellites can operate without interfering with each other's transmissions, and how much space traffic can operate before reaching unacceptable operating conditions.[14] A capacity then acts as an upper limit in some way, typically something one designs rules and best practices to avoid reaching. In none of these cases is the capacity truly a physical limit on how many satellites can "fit" in space, but rather ways that they can interfere with each other's operations.

Table 1: Environmental Stressors and Associated Negative Effects

Stressor	Short-term Effect	Long-term Effect
Increase in space activity, large constellations, mass-produced satellites	Errors, design flaws causing failures to have amplified effects	More mass that can end up as debris
Concentration of satellites for large constellations	More collision avoidance for other operators	Amplified debris-generation potential for satellite failures
Larger number of satellite operators across more countries	Coordination between systems more complex	Differing debris mitigation requirements can cause operating difficulties for U.S.
Increase in number of derelict objects and debris, such as rocket bodies	Strain on tracking systems, increased collision avoidance maneuvers, decreased launch opportunities	Increased satellite degradation and loss rates, faster self-perpetuating debris growth

Orbital debris that could result from poor management of these environmental stressors could affect operations in several ways (Figure 2). An obvious negative effect is a satellite being hit by debris too small to track and avoid. The U.S. Space Force's Space Surveillance Network can track objects roughly 10 cm (the size of a softball) and larger in low Earth orbit (LEO). Active satellites can avoid objects of this range, but accidental impacts with objects in this range would result in catastrophic collisions that generate large amounts of additional debris. Smaller debris, from about 1 to 10 cm, cannot be reliably tracked but would likely end a satellite's mission if it were to hit the satellite's body. Debris smaller than 0.5 to 1 cm might disable or degrade a satellite.

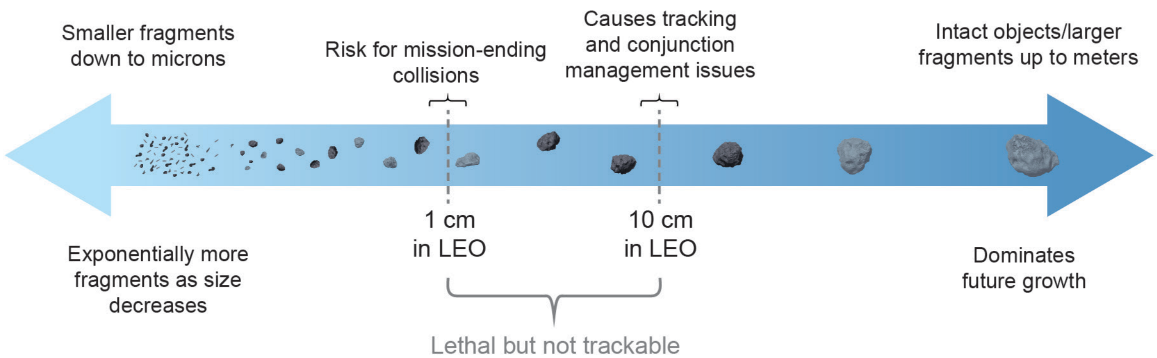


Figure 2: Debris effects by size.

In addition to some of the immediate effects on satellite operations, congested space could also produce longer-term effects on the environment itself. Space could be so populated that accidental collisions between objects occur, which could generate debris more quickly than can be removed by natural forces, such as atmospheric drag. In this situation, the debris population increases on its own. This is colloquially known as the "Kessler Syndrome," named after one of the NASA scientists who first proposed this potential scenario.[15] Several accidental collisions between tracked objects have already occurred, but it is unclear if debris production is currently outstripping natural removal. If the Kessler Syndrome were to begin, the effect would likely be initially very slow but also difficult to stop once it was clearly noticeable. In such circumstances, a large amount of derelict mass on orbit, which was enabling the collisions, would need to be removed to prevent continued accelerated debris growth. The removal of potentially tens of thousands of tons from orbit would be extremely difficult to execute considering technical, economic, and political challenges.

Location Matters. The congestion of the space environment will generally affect the risk of conjunctions and collisions, but there are parameters that can help mitigate these risks. The location of the traffic, and specifically altitude, weighs heavily on the risk of debris generation. When large constellation operators place many hundreds or thousands of satellites in orbits in a narrow altitude range, they can design and control their systems to avoid collisions between the constellation members. Given, as noted, that managing operations can become more challenging when multiple operators occupy orbits that are close to each other, coordination and communication between the operators is critical to avoid collisions. This is an important consideration for any owner when selecting an operational orbit and not limited to just avoiding other operators. There are also regions in space that contain higher concentrations of dead satellites and debris from breakup events, all of which are not maneuverable. Dead satellites and debris will never avoid conjunctions due to their lack of maneuverability. Any future breakup events from accidental explosions or collisions also have the potential to add significant amounts of debris to an orbit, amplifying these problems for any other satellites operating nearby.

All orbits are not created equal though. The problem of debris proliferation is worse at higher altitudes because there is no natural mechanism to remove the debris from orbit. At lower altitudes, the Earth's atmosphere is dense enough to cause objects to lose energy, lowering their orbits and causing them to reenter the Earth's atmosphere in a relatively short amount of time, some even in a matter of weeks. But the density of the atmosphere drops off exponentially as altitude increases, and debris orbiting at 700 km or higher can remain in orbit for decades. In higher orbits, debris can remain for hundreds or thousands of years. This is why altitude, or time on orbit, plays a critical role in determining an object's risk to the environment.

Mass and Size. In addition to how many objects there are and where they are, each individual object has characteristics that make it more or less likely to cause a risk to active satellites. Bigger objects are bigger targets, so the cross-sectional area or configuration of an object will affect how likely it is to be involved in a future collision. For example, a satellite with very large solar arrays or appendages that stretch out far from the main spacecraft body will pose more risk than a compact satellite with nothing sticking out. A large scientific observatory satellite will have a much higher collision probability over its life than a small CubeSat in a similar orbit.

In the unfortunate event of a breakup, whether it be a collision between two objects or a single object explosion, mass turns out to be a key parameter. The reason is that the mass of the object or objects directly correlates to the energy of a collision and how many debris fragments can be generated. More mass means more potential debris fragments, and more debris fragments means more objects that could potentially collide with other satellites in the future. From a debris perspective, a satellite is essentially a set of debris waiting to be released. For this reason, the mass of objects left on orbit is one of the most important parameters for understanding the effect of debris on sustainability.

Developing a Scalable Approach to Mitigation

Debris mitigation approaches generally have some cost associated with them whether it is higher reliability for certain systems, expenditure of propellant for disposal, or maintaining operations after mission completion. It is important to quantify the benefits of debris mitigation practices (or lack thereof) to identify those that are most effective and determine the appropriate levels at which they must be implemented.

As previously discussed, an approach to controlling orbital debris risk in LEO is to reduce or eliminate the accumulation of inactive mass on orbit. This can be done by reducing the amount of time objects spend on orbit (which is another way to say decrease the altitude because objects at lower altitudes will spend less time on orbit) and reducing the concentration of inactive objects so they are not as close to each other. So how does one put that principle into mitigation practice?

Disposal of Satellites

One good practice is for satellites to dispose of themselves at the end of their missions, removing themselves from heavily used regions of space. In LEO, to minimize the time nonfunctional satellites remain a collision risk, the Inter-Agency Space Debris Coordination Committee issued a limit of 25 years in which satellites could remain in a protected orbital region before being disposed or reentering the Earth's atmosphere.[16] Typically, a post-mission disposal (PMD) time requirement is accompanied by a minimum success rate because it is not currently possible to design satellites with perfect reliability. The rate in the current U.S. Government Orbital Debris Mitigation Standard Practices (ODMSP) is >90%.[17] This success rate requirement limits the number of satellites that could accidentally end up in long-lived orbits that are dangerous for the environment.

Rules to limit reentry time directly, like the 25-year rule, are already in place and should continue to be enforced and refined based on the state of the environment. Refinement may mean shortening that duration with increasing traffic as has been proposed by the FCC for large constellations in LEO. Some countries are moving towards even lower timelines than 25 years and a growing number of commercial companies have voluntarily pledged to abide by as low as 5 years.[18] A possible unintended consequence of a shorter disposal duration rule is that disposed satellites will be more concentrated in a narrow altitude range, increasing the collision probability in that range. Some operators have found success with maintaining control of their satellites during the post-mission disposal phase or even intentionally "driving" them down to the atmosphere. This method is referred as Control-To-Reentry (C2R) and enables a satellite to avoid large collisions as it deorbits. With the proliferation of large constellations in LEO, this approach may become a critical tool to complement the disposal duration rules.

Active debris removal, also known as orbital debris remediation, offers another means of removing large, already inactive objects that are currently in the environment. Similar to highly reliable post-mission disposal, this reduces the amount of inactive mass on orbit. Although the process of grabbing and removing inactive objects is much more expensive than properly disposing of a satellite at the end of its mission, it is the only means of removing already inactive mass from orbit. There is also an ongoing debate within the community over the relative priority of removing large (massive) debris objects, which will reduce population growth over the long term, and removing small, untracked debris objects, which will reduce the current collision risk to active satellites.

As previously discussed, the longer a satellite is left on orbit, the greater the chance it collides with another object and the longer other operators must avoid it. The sooner inactive mass can be moved out of orbit, the better. Ultimately, a high PMD success rate is the best way to reduce debris risk, ensuring a high likelihood the uncontrolled mass is moved away from operational orbits and its time on orbit is shortened. Ensuring a high PMD rate, as high as possible, is the best way to contribute to a sustainable future in space, but measuring the actual rate of PMD success is of course a lagging indicator.

Launching Efficiently. There are other actions that can be taken, particularly by large constellation operators, to continue tipping the balance in favor of sustainability. Extending satellite operational lifetime (but not in a way that sacrifices a high PMD success rate) means that constellation replenishment does not need to be done as often. That means fewer launches and fewer disposals, which also means fewer chances for failures that may generate debris. This and other actions that manage the proper disposal of upper stages are critical as poorly managed launch vehicle disposal can be as much or more of a risk than the constellation itself. In a large constellation of thousands of satellites, a few extra years of operation per satellite adds up to a significant reduction in potential debris mass. This, however, may run contrary to the way new constellation operators conduct technology refreshes of their systems. Smaller, cheaper satellites are the new norm, and a rapid replacement strategy to keep up with the latest technologies is the business model.

As satellite size and mass shrink, and as launch vehicle capability increases, more satellites can be deployed with fewer launches. Most launch vehicles have some components that will become on-orbit debris after deployment, so fewer launches to replenish and maintain a constellation means less potential debris. Launch providers can reduce the number of components left on orbit and use propulsion to reenter the upper stage in a controlled manner immediately after they separate from their payloads.

Increased Communication and Coordination Among Operators. Increased traffic in space, especially in narrow regions as with large constellations, necessitates better communications among operators. Typical satellite operators can coordinate passage through or near a large constellation if the large constellation operator is diligent about providing information on the current and near-future locations of its satellites. This is particularly important as most large constellations execute frequent maneuvers to maintain constellation geometry. Without foreknowledge of maneuvers, tracking a large constellation’s satellites accurately enough for conjunction management via an external tracking system becomes difficult.

This issue is significantly amplified if two large constellations are operating in close proximity to one another. In these cases, communication is critical because thousands of satellites will be interacting and may be trying to avoid each other through potentially incompatible automated systems. As of publication, existing large constellations have been good about communicating with each other and other satellite operators, even including sharing details of their automated conjunction management systems. China, however, has recently started deploying its own large constellations, some of which are planned in close proximity to existing and planned constellations from other countries. Historically, Beijing has been far less communicative about their satellite operations, which could be particularly problematic when it operates large constellations.

A Scalable Approach. These mitigation practices can be modeled by simulating space traffic and breakup events and projecting the resulting environment into the future. By varying input parameters (such as the PMD duration, PMD success rate, operational lifetime, satellites per launch, etc.), these modeling techniques can provide policymakers the analytical evidence needed to determine how to apply effective space debris mitigation rules.

The many mitigation measures available can be used to develop scalable debris mitigation rules, where larger systems that present a much higher risk to the environment than smaller single-satellite systems would be required to implement more rigorous mitigation techniques to comply with the rules. Such a scalable approach would need to strike a balance between the requirement for more stringent rules to ensure sustainability and the difficulty of implementing the techniques. Smaller resource-constrained missions will likely have more difficulty with reaching shorter duration disposal orbits or achieving higher PMD reliability rates, but the very large systems will likely have the resources and capabilities to do so. Space environment projection modeling will be very important for testing and comparing various approaches to scalable debris mitigation rules.

Sustainability in a Contested Environment

A conflict in space could exacerbate stressors to space sustainability. The worst long-term debris problems can occur where there are large numbers of both intact objects and smaller objects. The larger objects, such as constellation satellites, provide the mass to create new debris and enhance the self-perpetuation of debris. An exchange of DA-ASATs, for example, could generate more small debris that could trigger the breakup of the larger objects. Based on the Chinese and Russian ASAT tests, each future DA-ASAT event would be expected to produce at least thousands of pieces of debris, pieces which would be large enough to fragment a satellite. Another means of creating more disabled satellites is through impacts with the smaller debris created in high-energy ASAT intercepts. This debris from approximately 1 to 10 cm is too small to track and avoid, but it is likely big enough to disable an operational satellite even if it does not completely fragment it.[19] A typical ASAT engagement could be expected to generate hundreds of thousands of these fragments. This, again, adds to the number of potential debris-creating objects in orbit.

Cyberattacks on satellites could disable a large number of assets, increasing the number of intact objects that cannot maneuver. Disabled satellites would be unable to avoid collisions, increasing the chance of debris-generating events. The more disabled satellites, the greater risk of debris generation, although likely on a longer timeline than with destructive ASAT attacks.

Although a large-scale ASAT attack would have devastating environmental consequences over the long run, it would be an extremely unreliable tactic for intentionally disabling a constellation on a tactically relevant timeline. An example of this effect is the 2009 collision between an active Iridium satellite in a constellation and a dead Russian satellite. While other satellites have maneuvered to reduce risk of conjunction with debris from this collision, there was no short-term loss of other satellites in the constellation. The reason such a large-scale attack would not immediately wipe out a constellation of satellites is that space is big compared to the size of satellites and debris, so even a large amount of debris occupies only a small amount of the volume of space it passed through. Additionally, satellites in a constellation typically do not operate at exactly the same altitude, even if in similar operational shells. Orbital perturbations move the satellites up or down by kilometers on a single orbit, and station-keeping typically allows some variation in orbits so regions where fragmentation debris is concentrated after a breakup are not encountered by most of a constellation. Even though it is quite likely that other satellites would be hit by the debris over time, analysis shows that the increase in satellites lost due to secondary and tertiary collisions would be slow and likely smaller than the number of satellites directly attacked in a major conflict and to the amount of debris produced from those first-generation impacts. Although the short-term debris effects of kinetic strikes in space may be less than expected, the consequences would be severe on a longer time scale. It would also be nearly impossible to target these effects against one specific adversary's satellites, especially in highly used orbital altitudes where satellites from many countries and constellations all operate.

Conclusion

Successfully controlling the orbital debris environment is a truly global problem requiring not only U.S. adherence to rules and practices, but also that all space-faring organizations follow good mitigation practices. Important among these is avoiding the testing of destructive anti-satellite weapons.[20] Because orbital debris effects are cumulative, one other way to mitigate the effects of a potential conflict in space is to lessen debris risks pre-conflict. The fewer large objects that are in orbit and unable to maneuver, the fewer potential sources of new debris. Maintaining strict adherence to post-mission disposal requirements and encouraging all space-faring organizations to do likewise would be a valuable step. This is generally a good idea and made even more important by the potential for conflict. Other approaches, including improving communication and coordination among satellite operators, launching efficiently, and C2R and active debris removal would all be helpful.

Governments should also incorporate margin between the environment targeted by debris mitigation rules and that which is considered acceptable. Not only does this provide some safety with respect to the uncertainties in anticipating how the debris environment will grow, but it also provides some robustness to withstand the effects of contested situations and their consequences. Any efforts to define capacity for satellites should factor in the possibility of conflict.

There are also approaches specific to lessening the effects of a conflict in space. As noted, kinetic direct ascent ASATs could produce devastating long-term effects on the space environment, even if not an effective military tactic to destroy an adversary's constellation. Along these lines, measures like the U.S.-led moratorium on direct ascent ASAT testing,[21] which as of August 2024 had 37 adherents and could disincentive states from pursuing destructive, debris-producing ASATs.[22]

The combination of congested space operations and the potential for contested space scenarios has increased the importance and complexity of maintaining a sustainable space operating environment. Given the complexity of the challenge, policymakers should carry out steps now to help ensure a sustainable environment over the long term. These should include both improved debris mitigation measures to manage the effects of the ever-growing operational satellite population and efforts like the U.S. moratorium on direct ascent ASAT testing to limit the impacts of contested space.

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