An Overview of NASA's Newest Engineering Model, ORDEM 4.0

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Abstract

Since the mid-1990s, one of the most important products produced by the NASA Orbital Debris Program Office (ODPO) has been the Orbital Debris Engineering Model (ORDEM). This series of models distills down our knowledge of the orbital debris environment to compute debris fluxes on satellites in a given orbit. This information can be used by spacecraft designers and operators to design missions for better protection against the debris environment. The current version of the model is ORDEM 3.2, but the ODPO is working on the next generation of ORDEM, to be designated ORDEM 4.0. ORDEM 4.0 will include many known features from previous models, such as the ability to input a spacecraft orbit and time and to compute the flux as a function of debris size, impact speed, impact direction, and debris material densities, as well as uncertainty information on the flux. ORDEM 4.0 will update debris populations using the most recent measurements, including radar observations by the Haystack Ultrawideband Satellite Imaging Radar (HUSIR), NASA's Goldstone radar, data from the new Space Surveillance Network Space Fence, and observations of Geosynchronous Earth Orbits (GEO) using the Eugene Stansbery-Meter Class Autonomous Telescope (ES-MCAT). The latest *in situ* impact data from returned spacecraft surfaces will be used. In addition, ORDEM 4.0 will introduce a parameterized debris shape model based on laboratory hypervelocity impact tests, such as DebriSat. This will allow analysts to implement shape characteristics in their damage equations and more accurately predict impact damage risk by debris of different shapes and orientations. This paper provides an overview of some of the new features forthcoming in ORDEM 4.0 and a status report on its development.

1 Introduction

The NASA Orbital Debris Program Office (ODPO) began development of the Orbital Debris Engineering Model (ORDEM) in the mid-1980s in support of the Space Station Program Office. The ORDEM software currently serves as the primary tool to provide a timely, validated model of the human-made orbital debris environment. It facilitates modeling assessments by spacecraft owners/operators, as well as ground-based observation planning. Initial manifestations of the model included analytical solutions representing the debris environment [1]. The first computer-based version of ORDEM was released in 1996 as ORDEM96 and pioneered the use of debris population ensembles characterized by altitude, eccentricity, inclination, and size [2]. ORDEM2000 replaced the curve-fitting approach with a finite element representation of the debris environment [3]. ORDEM 3.0 represented a significant upgrade in terms of model features and capabilities [4]. It extended the model to the geosynchronous orbit (GEO) region (up to 40,000 km), which enabled analysis of more varied orbits – such as geosynchronous transfer orbits (GTO) and other highly elliptical spacecraft orbits – and sensor orientations. Additional upgrades included expansion of observation program datasets in underrepresented regions and the addition of uncertainties on the reported orbital debris flux. Most significantly, ORDEM 3.0 included a distribution in material density of orbital debris fluxes [5].

The orbital debris environment is dynamic and must be periodically updated. As newer datasets become available, they provide more information on the evolution of the orbital debris environment. In addition, newly developed data analysis techniques can be applied to both new and legacy data to improve the assessment of orbital debris populations. ORDEM 3.1 was created to include the same capabilities as ORDEM 3.0 and incorporate updated datasets available to NASA for both constructing and validating the modeled orbital debris populations [6]. New approaches to analyzing the available data were also implemented for the large breakup clouds (*Fengyun*-1C [FY-1C], Iridium 33, and Cosmos 2251), *in situ* impact data, and the GEO population.

On 15 November 2021, the Russian Federation tested a direct-ascent anti-satellite weapon on their Cosmos 1408 spacecraft [7]. The resulting large cloud of debris was of sufficient size and concern that the ODPO created an update of the ORDEM model (ORDEM 3.2) to include the effects of this new cloud. This update was released in early 2022 [8].

For the next generation of ORDEM models – ORDEM 4.0 – several changes are being planned. The most important change is the inclusion of debris shape. Other updates include expanded density families, a new approach to binning debris populations (both spatially and by size), an update to the breakup model to incorporate shape, and, as with previous versions, more recent datasets for building and validating model populations.

2 Debris Shape

Multiple, internal NASA reviews of the ORDEM model through the years indicated one of the major limitations identified was the over-simplification of the shape model – all objects were assumed to be spheres. This has long been a simplification with all the ORDEM models. How to incorporate ideal spherical debris has led to several crude assumptions, including how to incorporate material density and mass into the spherical debris (is it better to model as “hollow” low-density spheres or as smaller spheres at the material density?). The original plan for ORDEM 3.0 was to include debris shape; however, the problem proved too difficult to address at that time due to data and theoretical limitations. These included incomplete shape information from breakup tests and models and a lack of theory on how to incorporate the information into damage equations.

As a result, it was determined by the ODPO that the most important change for ORDEM 4.0 would be a debris shape model. This effort has been aided by the unprecedented level of detail in the analysis of the DebriSat debris fragments, including shape information [9, 10]. The problem that has always presented difficulty in attempting to parameterize shape is due to the complexity of ensuring consistency of shape, dimensions, volume, mass, and mass density or “effective” density.

Determining damage equations using spherical projectiles, aside from practical test procedures, has the benefit of limiting the possible range of impact parameters. Besides the intrinsic properties of the sphere (diameter, mass) and the impact velocity, only a single impact angle (the angle with respect to the surface normal) needs to be tested and modeled; however, when debris shape is included, the number of impact geometries grows. A generic three-dimensional object needs four impact angles to uniquely define the configuration. Adding so many dimensions can make laboratory testing intractable. Unfortunately, there is no way to reduce the problem to two angles, but by choosing an object with axial symmetry, the problem can be reduced to three angles: the normal angle, the tilt of the object’s symmetry axis to the velocity vector, and the yaw of the symmetry axis around the velocity vector (see Fig. 1).

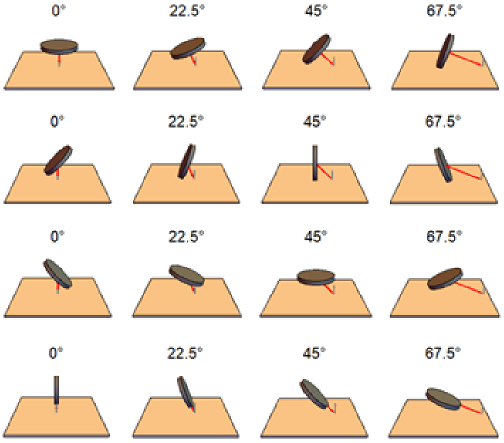

Fig. 1. This diagram illustrates examples of the many impact angle configurations that can occur with a debris object in the shape of a right circular cylinder (RCC, in this case, a disk). Note that this selection does not include the effects of yaw about the velocity vector [11].

One possible debris shape with axial symmetry is a prolate or oblate spheroid. This has the benefit of being a variation on a sphere; however, the manufacture of these shapes for hypervelocity impact tests has proven difficult, especially for small impactors. Instead, for ORDEM 4.0 the shape with axial symmetry chosen is a right circular cylinder (RCC), defined by its length-to-diameter ratio (L:D). A cylinder with L:D > 1 is a rod shape, and one with L:D < 1 is more disk-like. This shape is relatively easy to manufacture by cutting cylindrical rods or wires of material. The actual “shoe-horning” of various debris shapes into these categories is a complex subject [9], but it allows debris shapes to be parameterized and stored in a computer model in a tractable fashion.

L:D ratios for the DebriSat fragments span a continuum of values, from long rods, to nugget-like squat cylinders, to plate-like debris. To simplify the model storage of shape information, the model takes advantage of the fact that the debris falls into broad groupings of L:D ratios. In the model, these L:D ratios are grouped by a single median value of L:D to define an entire shape family.

While these assumptions may seem to oversimplify a very complex shape distribution, it is useful to keep in mind that there is currently no engineering model for orbital debris that explicitly includes shape. The inclusion of shape represents a signal achievement in capability and accuracy. Therefore, these RCCs represent a major improvement in the ability to compute probabilistic debris risk.

One challenge with testing non-spherical shapes in a hypervelocity impact test facility is that in practice it is impossible to control the flight angle of non-spherical shapes as they hit the target. Instead of trying to control the angle of impact, cameras can be used to measure the randomized orientation as the impactor hits. Using several tests with various measured random orientations allows the analyst to calibrate the damage hydrocodes and determine a damage equation for an expanded set of orientations of the RCC [12]. These damage equations are then referenced to those determined by impacts with spherical debris (analogous to L:D ~1) to come up with a comprehensive shape-dependent function. There are limitations, however, as very long rods and very thin disks are difficult to test in the lab. Nevertheless, with only a modicum of new tests with RCCs, new, improved damage equations can be formulated that leverage work already done with spherical debris.

3 Model Changes

This section will outline a number of other changes planned for, or being implemented in, ORDEM 4.0.

3.1 Density Families

One of the findings in analyzing the U.S. Space Transportation System (STS), the Space Shuttle, data for the ORDEM models was the presence of titanium debris in the Shuttle radiators, assessed as metal and not paint pigment. Titanium has a density of 4.5 g/cm^3, which places it mid-way between the previous categories of Medium Density (aluminum, 2.8 g/cm^3, being representative) and High Density (stainless steel, 7.9 g/cm^3, being representative). In recognition of this non-trivial component of the environment, Medium Density is now divided into two density classes Medium-Low Density (2-4 g/cm^3) and Medium-High Density (4-6 g/cm^3).

A second new class of material density has been introduced by the analysis of the DebriSat data [10]. The target mock satellite was deliberately created to be representative of more modern spacecraft, so it included large amounts of carbon fiber-reinforced plastic (CFRP), with density 1.46 g/cm^3. As this debris population has a singular density within the Low Density category (0-2 g/cm^3) and exhibits unique shape characteristics it is now incorporated as its own mass density class for ORDEM 4.0.

Another change was to internally model the STS impact features using a population of paint particles. In the past, these were included with Medium Density; however, these particles are identified separately in the STS database, and they are believed to have unique sources and unique debris shapes (assumed to be “nuggets” when small and flat disks for larger sizes), which affect their damage equations. In ORDEM 4.0, these populations are implicit in the model, included in the Medium-Low Density populations, but with their unique shapes preserved.

3.2 Size Binning

One of the features of the ORDEM 3 family of models is that the size distributions were divided into half-decade bins for storage and computation purposes. Careful analysis showed that doubling the number of size bins to four per decade in size, from 10 µm to 1 m, provides a better model for the inflection points of the various populations contributing to the total flux at all sizes.

A careful study was done with ORDEM 4.0 to determine if size (actually Characteristic Length [13]) was still a useful model parameter, or if it would be more appropriate to switch to another parameter, such as mass. After much discussion, the ODPO determined that there was no major technical benefit to using either parameter. Therefore, the decision was made to stay with a size parameterization for consistency with past and current models, guidelines, and requirements.

3.3 IGLOO Binning

One inefficiency with previous ORDEM models is the binning of the IGLOO file – the breakdown of the debris flux in terms of a two-dimensional direction and relative velocity in the spacecraft frame. Previously, binning in equal displacements in azimuth and elevation was used, but this meant that the model was computationally expensive and used excessive storage allocation computing fluxes near the poles (typically the nadir and zenith directions), while most of the debris flux occurs (at least for circular orbits) in the local horizontal plane (the “equator” of the IGLOO). After examining several options, a formulation of the IGLOO that preserves solid angle was adopted using the method of Arvo [14]. The Arvo method maps squares on a cube onto a unit sphere in such a way that each of the elements has the same solid angle and area on the unit sphere. This method is shown in Fig. 2 and Fig. 3. This method is much more versatile in that it can handle any flux direction pattern, while saving in computation time and storage.

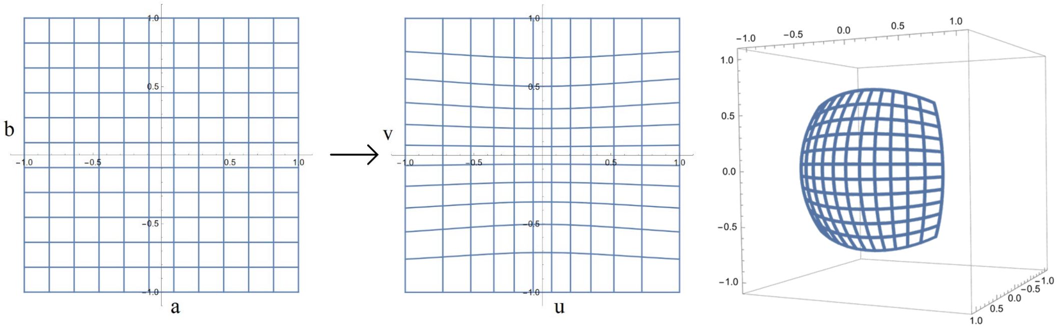

Fig. 2. The Arvo mapping takes a series of square segments on a cube face and maps them to the surface of a unit sphere. Each of the elements on the sphere face has the same area and subtends the same solid angle.

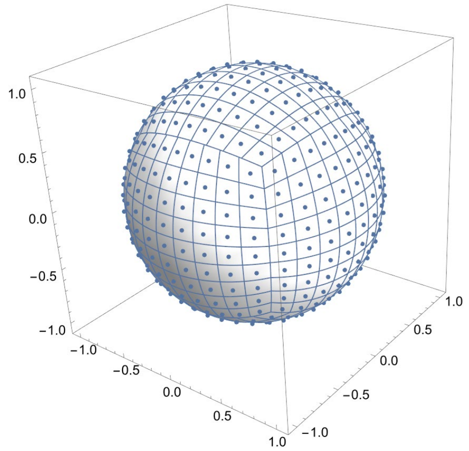

Fig. 3. The final Arvo map is composed of mapping all six sides of the cube. When the ORDEM IGLOO is implemented in the BUMPER risk assessment code, the flux is mapped to the central point of each element.

4 ORDEM 4.0 Model Populations

The ORDEM series of orbital debris environment models are primarily data-driven, and reliable data are required to build a realistic and valid model. Table 1 summarizes the ground-based and *in situ* datasets used for building and validating the ORDEM 4.0 model, including their respective calendar year (CY) range of measurements. To place these measurements in context with regard to ORDEM 3.1/3.2, Table 2 contrasts population build sets used for ORDEM 3.1 [6] and ORDEM 4.0.

The fundamental dataset for ODPO modeling efforts is the ODPO-maintained space traffic database, which characterizes satellites launched – including known and/or estimated orbital elements and physical characteristics – as well as details of known historical breakups and maneuvers. The space traffic database is largely predicated upon the U.S. Space Surveillance Network (SSN) catalog, which is considered nearly complete for objects larger than approximately 10 cm in LEO and 1 m in GEO. The yearly space traffic is propagated forward in time using the NASA low Earth orbit (LEO)-to-GEO Environment Debris (LEGEND) model [15]. The LEGEND model provides the baseline for most sub-populations in ORDEM. The historical population (*i.e.*, initial reference population) for ORDEM 4.0 covers launches from 1957 to 2022 inclusive.

Table 1. Datasets used for building and validating the ORDEM 4.0 model populations. The CRS acronym indicates NASA Commercial Resupply Services (CRS) contract flight returned surfaces.

Data Source	Year(s) of Coverage – Build	Year(s) of Coverage – Validation
SSN Catalog	1957 – 2022	2023 and after
HUSIR	2016 – 2022	2023 and after
HAX	2018 – 2020	N/A (no data available after 2020)
Goldstone	2016 – 2022	2023 and after
STS windows and radiators	1995 – 2011	N/A
HST WFPC2	N/A	1993 – 2009
ES-MCAT	2020 – 2022	2023 and after
MODEST	N/A	2013 – 2014
HST MLI	N/A	1990 – 2009
CRS	N/A	2017, 2019
PMA-2 cover	N/A	2013 – 2015

Table 2. Datasets contrasted: the annual coverage of ground-based and *in situ* data used to build the ORDEM 3.1 and 4.0 models, including relevant size limits

Data Source		Size Limit(s)	Years covered ORDEM 3.1	Years covered ORDEM 4.0
In situ	STS radiators and windows	10 – 300 µm	1995-2011	1995-2011
Radar	Goldstone	3 – 8 mm	N/A	2016-2022
	HUSIR 75E	>5.5 mm	2013-2015	2016-2022
	HUSIR 20S	>5.5 mm	2015	2016-2022
	HAX 75E	>3 cm	N/A	2018-2020
	SSN Catalog	>10 cm (LEO)	1957-2014 (LEO)	1957-2022
		>1 m (GEO)	1957-2015 (GEO)	
Optical	MODEST	30 cm – 1 m	2004-2006, 2007-2009	N/A
	ES-MCAT	30 cm – 1 m	N/A	2020-2022

Fragments from confirmed historical fragmentation events down to 1 mm in size were created using a special version of the NASA SSBM, which incorporates fragment characteristics, including material density and shape, based on laboratory impact tests. For future projection, objects were added to the population assuming a repeat of the previous 8-year launch traffic cycle and a post-mission disposal success rate of 90% for rocket bodies and spacecraft. Future collisions and explosions were modeled statistically. Objects greater than 10 cm were allowed to collide according to the “cube” collision assessment algorithm in LEGEND [16]. Probabilities of explosion for intact objects were assessed using an empirical time-dependent explosion rate model. To build a statistically complete representation of debris populations, the initial reference population was adjusted based on data from instruments optimized to observe debris with sizes smaller than the SSN cataloging threshold, including ground-based and *in situ* sensors.

4.1 Radar-based Populations

The Haystack Ultrawideband Satellite Imaging Radar (HUSIR) and Goldstone Orbital Debris Radar are the primary sources of radar data utilized by the ODPO [17]. HUSIR (previously Haystack) is a 37 meter dish, monostatic X-band radar operated by the Massachusetts Institute of Technology Lincoln Laboratory, which provides data for LEO debris larger than approximately 5.5 mm. Goldstone, a bistatic X-band radar, is operated by NASA's Jet Propulsion Laboratory (JPL). It uses a 70 m- and 34 m-diameter dish for the transmit and receive antennas, respectively, and extends LEO coverage of debris down to approximately 2-3 mm. Both HUSIR and Goldstone operate in a staring mode for debris observations, pointed at a fixed point in space with respect to the local topocentric coordinate system while objects pass through the radar beam. Composite data from HUSIR and Goldstone over CY2016–2022 were used to scale the initial LEO populations modeled by LEGEND. Special populations in LEO, including specific debris generation events, anomalous non-explosive events, and the sodium potassium (NaK) population, were modeled and scaled independently, as discussed in Section 4.1.1.

4.1.1 Special populations

ORDEM 4.0 includes several "special populations" of objects, so designated based on certain criteria, including unique cloud attributes, a notable release mechanism, anomalous or significant production of fragments, or lack of a readily identifiable source or production mechanism. These special populations are summarized in Table 3 and include custom, large breakup events; the major breakup clouds from the *FY*-1C and Cosmos 1408 antisatellite tests and the Iridium33/Cosmos 2251 accidental collision; debris from shedding events by the SNAPSHOT vehicle and Transit series of spacecraft; the so-called "82-degree cloud" [18]; and the NaK droplets that were released from Soviet Radar Ocean Reconnaissance Satellites (RORSATs).

Table 3. Special debris populations modeled in ORDEM 4.0

Description	Estimated Parent Altitude and Inclination at Event Date	Event Date
Custom large breakup events	Event-specific	Event-specific
Chinese Anti-satellite Test (*i.e.*, ASAT, FY-1C)	~850 km, 98.8°	11-Jan-07
Iridium 33 / Cosmos 2251 collision	~790 km, 86.4° / ~790 km, 74.0° respectively	10-Feb-09
Cosmos 1408 Anti-satellite Test	~480 km, 82.6°	15-Nov-21
SNAPSHOT (1965-027A) satellite debris event	~1300 km, 90.3°	Multiple events and a single large event in 1984
Transit constellation satellite debris events (33 events)	~1100 km, 90°	Deposited at end-of-mission+ 20 years, per vehicle
"82° cloud"	~1010 km, 82.9°	Deposited over 2004-2014
NaK	900-1000 km (one at 700–760 km), ~65°	Assumed steady state

These special populations were scaled statistically based on comparisons to radar data. The SNAPSHOT/Transit and 82° events are anomalous in that they appear to be producing and/or slowly shedding off mass over time. These events were initially modeled using the NASA SSBM with a maximum separation velocity of 10 m/s, then scaled based on radar data.

The NaK model, like that used in ORDEM 3.1, was assumed for ORDEM 4.0 to be in steady state based on analysis of the HUSIR data and screening methods used for ORDEM 3.1 [19]. The NaK population is explicitly identified in the ORDEM population types due to its unique characteristics (*e.g.*, spherical shape and unique material density). Debris from all other events/sources are included within the other material density families.

4.2 *In situ*-based Populations

Data for building the ORDEM 4.0 debris population in the sub-millimeter size range in LEO are provided by the database of impacts to the STS orbiter vehicle (*i.e.*, the Space Shuttle crewed component), as archived by NASA's Hypervelocity Impact Technology group. The database contains information on impacts to the Space Shuttle, categorized by mission and surface. Data on impacts to the Shuttle windows (excluding the cargo bay windows) and radiators from STS missions 71 through 133 (1995–2011) were again used for building the ORDEM 4.0 small particle population [20]. Unfortunately, no analogous high-quality, large area sensors have provided *in situ* data since the cessation of the Shuttle program, so this data is still an important contributor to ORDEM 4.0, despite its vintage.

The STS window and radiator data approximately cover size ranges of 10 µm – 300 µm and 300 µm – 1 mm, respectively. The small particle population less than approximately 3 mm was modeled separately from the radar-based population using a special small-particle degradation model [21] that creates small particles assuming a production rate proportional to the surface area of a source body. The average production rate was calculated using an arbitrary initial production rate based on particle size, time interval, and the surface area of the source object. The initial size distribution was sampled randomly from a uniform distribution (in $\log_{10}$ space) between 10 µm and 3 mm. The newly created particles were simulated to be ejected from the parent body, so they shared the same orbit with the source body at the creation time, and their orbits were evolved over time under standard orbit perturbations. The predicted impact rate of these modeled particles on the STS for each mission (including year, epoch, and spacecraft orientation) was computed, and the number of predicted damage features of various sizes was calculated using empirical damage equations. The parameters of the production curve were adjusted to match the observed feature distribution from the STS impact database.

In situ data for ORDEM 4.0 validation includes the Wide Field Planetary Camera 2 radiator and Hubble Space Telescope (HST) multilayer insulation (MLI) surfaces used for ORDEM 3.1 validation but is expanded to incorporate more recent datasets from Pressurized Mating Adapter-2 blanket surface and CRS flight surfaces examined in 2022–2023 [22]. The CRS flights, employing the Space Exploration Technologies Corporation ("SpaceX") *Dragon* capsule, offer a timely and well-characterized source of exposed surfaces. Recent work has demonstrated the feasibility of using samples excised from the capsule's thermal protective surfaces for impact residue identification. The largest impact features from CRS-13 (2017) and -18 (2019) provide singular validation data points for these two years.

4.3 Optical-based Populations

Historically, the Michigan Orbital DEbris Survey Telescope (MODEST) was the ODPO's primary source of data for debris in GEO from the size limit of the SSN catalog (approximately 1 m) down to approximately 30 cm. Since 2020, NASA's Eugene Stansbery –Meter Class Autonomous Telescope (ES-MCAT), a 1.3-m telescope located on Ascension Island, has provided GEO survey data for building and validating

ORDEM populations [23]. Objects are filtered to determine those most likely to be GEO debris based on sizes and orbital parameters. In contrast to the radar-based populations, fragmentations are not explicitly included in the ORDEM GEO populations, but are implicitly included directly from the optical data; this approach prevents any potential overestimation of these fragments that are resident in the data. By extension, fragments from any unconfirmed or unknown GEO breakups that have not been modeled are also implicitly included.

5 Summary

The ODPO is currently developing ORDEM 4.0. While the final form of the model is still under development, several decisions regarding the structure and new features have been outlined in this paper. These include decisions on how to implement an IGLOO gridding with equal solid angle elements, a finer resolution on size binning of the populations, use of the DebriSat database to improve debris material shape information, and the implementation of new material density categories. The most significant updates for ORDEM 4.0 are the decisions regarding how to incorporate shape into the model. The decision to use right circular cylinders to approximate the shapes of debris will result in a major shift in how damage equations are tested, derived, and implemented in spacecraft risk computations.

Because the environment is dynamic, ORDEM 4.0 uses updated measurements, primarily from ground-based radars such as HUSIR and Goldstone for LEO and ground-based telescopes such as ES-MCAT for GEO. Unfortunately, there are no high-quality, large area, *in situ* data sources since the cessation of NASA Space Shuttle missions. Therefore, most of the small particle modeling is based on updated analyses of those data sets, although limited new datasets are used for validation.

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