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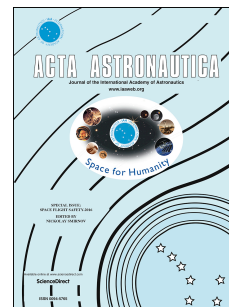


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Science Objectives of the MMX Rover

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Abstract

The Martian Moons eXploration (MMX) mission by the Japan Aerospace Exploration Agency, JAXA, will explore the Martian moons Phobos and Deimos. In addition to investigating the moons remotely and returning samples from Phobos, MMX will also deliver a small (about 25 kg) Rover to the surface of Phobos.

The payload of the Rover consists of four scientific instruments: RAX, a Raman spectrometer to measure signatures of the mineralogical composition of the surface material, NavCam, a stereo pair of cameras to investigate the terrain and allow for navigation, miniRAD a radiometer to measure the surface brightness temperature of both, regolith and rocks, and two WheelCams which will observe the wheel-surface interface, and thus investigate the properties and dynamics of the regolith. The cameras, will serve both, technological and scientific needs.

The rover will be deployed during the rehearsal phase of the landing operations for the main spacecraft and will thus land in proximity to the first sampling area. During its operational lifetime on Phobos (about 100 days), the in-situ measurements performed with the rover payload will provide scientific context for the returned samples, provide ground truth, study the surface heterogeneity and obtain information on the physical properties of undisturbed surface material. The MMX launch is planned for September 2024 and the Rover delivery is scheduled for 2027.

The Rover is a contribution by the Centre National d'Etudes Spatiales (CNES) and the German Aerospace Center (DLR) with additional contributions from INTA (Spain) and JAXA.

Keywords: Phobos, Martian Moons eXploration MMX, Rover

1. Introduction

The MMX Rover is a contribution by the Centre National d'Etudes Spatiales (CNES) and the German Aerospace Center (DLR) to the Martian Moons eXploration (MMX) mission by the Japan Aerospace Agency, JAXA, which will investigate the Martian moons Phobos and Deimos [1,2]. It will be delivered to the surface of Phobos to perform in-situ science but also to serve as a scout, gathering data to prepare the landing of the main spacecraft. The MMX Rover will deliver

information on the regolith properties by high resolution imaging (NavCams and WheelCams), measurement of the thermal properties with a radiometer (miniRAD) and Raman spectroscopy (RAX) [3,4].

The first observation of Phobos with spacecraft dates back to the 1970s, when Mariner 9 took images of the Martian moons. Since then several spacecraft have provided data from Phobos, both from orbit or from the surface of Mars [5]. The origins of Phobos and Deimos, however, are still not clear and various scenarios (e.g.,

capture or accretion around Mars after, for example, an impact) are currently discussed [6,7].

The MMX mission targets to solve this puzzle by measuring the properties of Phobos in great detail through measurements from orbit, on the surface of Phobos and by analysing the samples returned to Earth [2].

MMX is a sample return mission that includes remote sensing instruments as well as a rover, to be delivered to the surface of Phobos and operating there.

The rover will perform scientific measurements with its four science instruments for about 100 days. It will also for the first time demonstrate locomotion on basis of wheels on a low gravity body [3,8,9]. Mobility by hopping on the surface of Phobos was foreseen during the Phobos mission in the 1980s [10], but unfortunately, the spacecraft went lost before the hopper, PROP-F, which sometimes was referred to as “rover”, could be delivered [10,11].

Although the operational lifetime on the surface of Phobos is envisaged to be about 100 days, due to a lack of knowledge of the actual terrain at the landing site, it is difficult, to define a well based requirement for the minimum driving distance [e.g., 12]. The duration of rover operations after landing is restricted by spacecraft constraints (and, at some point by seasonal effects), rather than rover life-time per se.

2. Scientific Objectives and Instrumentation

The scientific objectives of the MMX rover complement and support the overall MMX mission, as is described in [2,4]. They complement the science which can be performed remotely with the instruments on board the main MMX spacecraft or the returned samples [13].

The rover instruments (see below) will focus on determining regolith properties as well as analysing the dynamic behavior of dust grains, surface processes, the geological history and the composition of Phobos and its thermal and mineralogical properties. The data set that will be obtained in-situ will provide ground truth and a geological context for the samples that are going

to be returned to Earth. They will help understanding the origin and history of Phobos.

During its operational lifetime the Rover will perform:

- Close-up and high-resolution imaging of the surface terrain
- Regolith science (e.g., geometrical properties like the grain size distribution, mechanical properties like surface strength, cohesion, porosity and dynamical properties)
- Measurements of signatures of the mineralogical composition of the surface material (by Raman spectroscopy)
- Determination of the thermal properties of the surface material (surface temperature, emissivity, thermal conductivity, layering)

This will allow to study the heterogeneity of the surface material and, thus, will also help the MMX landing and sampling strategy to be defined.

Characterization of the regolith properties shall also reduce the risk of the landing (and sampling) of the main spacecraft, as the touch-down strategy can be adapted accordingly. As a quick proxy to the surface mechanical properties, the rover has system accelerometers (MEMS, 16 g range) which record the impact accelerations (< 1 m/s velocity) after delivery by MMX.

Figure 1 shows the rover in fully deployed configuration from underneath with deployed legs and solar panels and the shutters for cameras, RAX and miniRAD open. The four instruments are listed in Table 1.

As an additional payload element, a passive Laser Retro Reflector (LRR), provided by ASI/INAF, is mounted to the rover.

Figure 2 shows the rover internal parts, including the Service Module (SEM), which is inside the chassis.

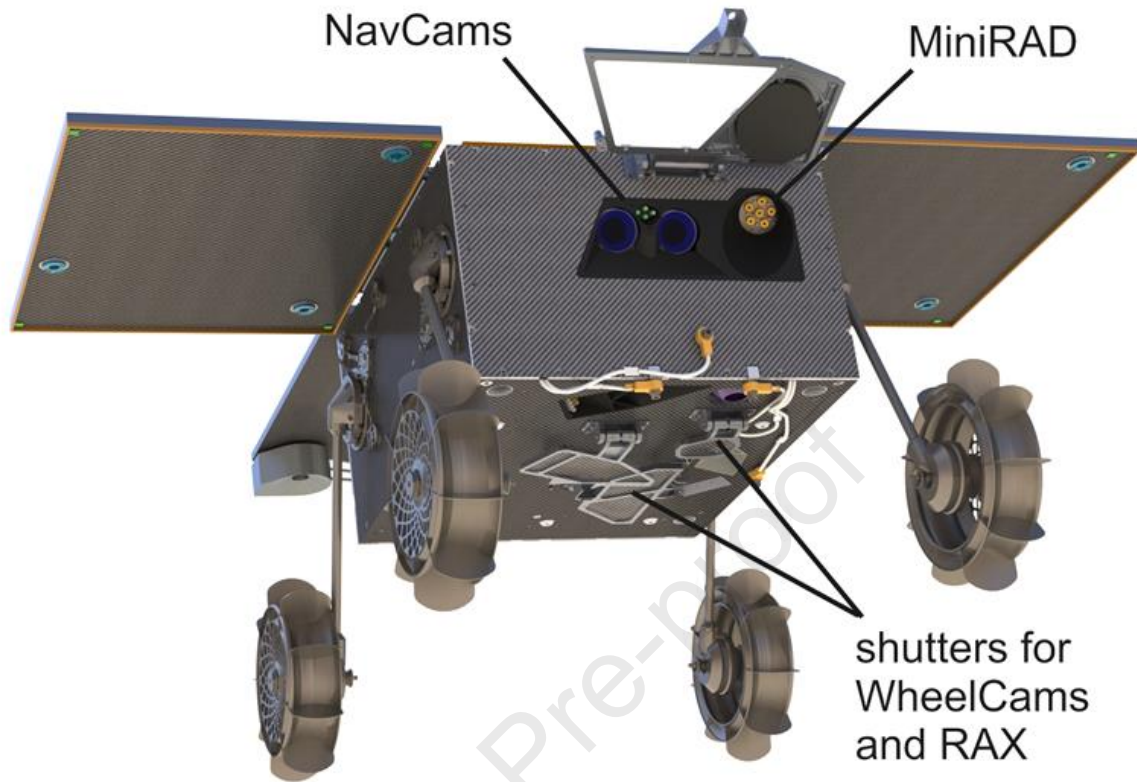


Figure 1: MMX rover, in on-surface configuration

Table 1. MMX Rover instruments

	type	Mass [kg]	PI institute(s)
NavCams	Stereo navigation camera	0.35	LAM, Marseille
WheelCams	Wheel camera	0.35	ISAE-SUPAERO, Toulouse
RAX	Raman spectrometer	1.51	DLR, Berlin; INTA, Madrid, UVa, Valladolid and Univ.Tokyo
miniRAD	Radiometer	0.34	DLR, Berlin

2.1. Navigation Cameras, NavCam

The NavCams, a stereo pair, looking in the driving direction, will be used for navigation but also to image the landscape and place some constraints on the level of heterogeneity of the regolith both in terms of composition and space weathering alteration with a higher spatial resolution as compared to the orbiter. Note that, unlike traditional rover navigation cameras, in order to keep the overall rover design compact and simple, and to avoid an additional mechanism, the

NavCams are not on a mast and have no pan nor tilt capabilities.

The optics have a wide field of view (120° corner-to-corner, 83° edge-to-edge) and depth of field from $\sim 35\text{cm}$ to infinity. With 1 mrad pixel field of view (center of field), the resolution is 1 mm at 1 m distance. Given the low height of the stereo-bench, useful information will mostly be acquired in the range up to 2 m in front of the rover. The 2048×2048 pixel CMOS detector has been developed by 3DPLUS under CNES contract [14]. Moreover, the detector of the NavCams is coated with a matrix of pixel-sized colour filters (Bayer filter) in RGGGB (red-green-green-blue: four pixels composing a Bayer matrix) configuration, allowing to see the landscape in colour. The stereo cameras are also equipped with LEDs to be able to operate at night under very long exposure times.

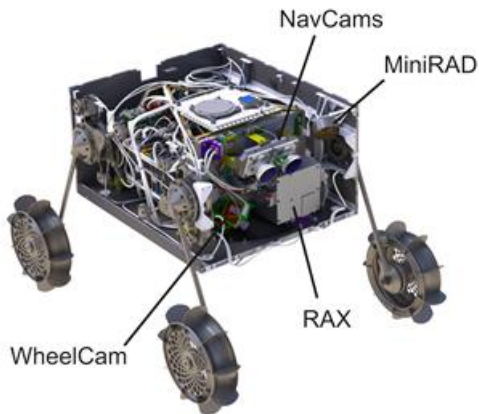


Figure 2: Rover illustration, showing internal parts including SEM, with NavCams and RAX.

The NavCams will provide context information for the remaining rover instruments and allow the rover to perform autonomous navigation at the surface of Phobos. Figure 3 shows the NavCams at the stereo bench at CNES.



Figure 3: View of the NavCams at stereo bench (image: CNES/Tardivel Simon, 2022)

2.2 Wheel Cameras, WheelCam

There will be two WheelCams on the rover, imaging the contact points of the wheels with the surface. The interaction of the wheels with the regolith and the structure and depth of the tracks will be imaged and even movies can be taken. The cameras are panchromatic and have a 2048 x 2048 pixel resolution and a spatial resolution of approximately 100 μm for 1 pixel at the center of the image. This resolution will be sufficient to characterise the size distribution of regolith particles above the resolution limit as well as the sphericity and angularity of larger particles. Such information is not only important for understanding the surface properties of Phobos, but this knowledge about the surface will also lower the risk of the MMX spacecraft landing.

The CMOS camera sensor for the WheelCams is identical to the one for the NavCams, but remains panchromatic (no Bayer filter). The optics are narrow and focus on a scene of about 20 cm diameter close to the wheel. LEDs will be used during driving to illuminate the scene as it will usually be shadowed by the rover body or solar panels. For each WheelCam, three additional LEDs, each illuminating at a different wavelength between 550 nm and 900 nm, will be used at night. These will provide colour information on the imaged regolith, both on the undisturbed surface but also in the trench created by the wheels.

Figure 4 shows both flight models of WheelCam and NavCam.

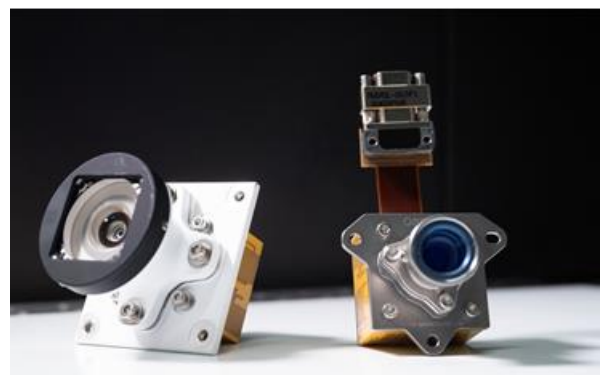


Figure 4: Flight models of NavCam (left) and WheelCam (right) (image: CNES/DE Prada Thierry, 2022)

2.3 Raman spectrometer, RAX

RAX (Raman spectrometer for MMX) is a compact, low-mass Raman instrument with a small volume, compared to similar instruments (RAX Spectrometer Module-RSM: $(98 \times 105 \times 83)$ mm³ / RAX Laser Assembly-RLA: $(51 \times 61 \times 19)$ mm³) and a mass of 1.51 kg, developed under the lead of DLR, with contributions from INTA/UVa, who provided the RLA, and JAXA/Univ. Tokyo, who provided the Autofocus Subsystem (AFS) [15,16]. RAX will perform Raman spectroscopic measurements to identify the mineralogy on Phobos' surface beneath the MMX rover. To do so, the rover will lower its body and decrease the distance to the ground until the RAX instrument reaches its working distance. Then, with the AFS, the RAX laser will be focused onto the rock or regolith in the field-of-view and Raman data is acquired from a spot of 50 μ m in diameter.

Measuring multiple positions on Phobos will give insight into the mineralogical composition and its heterogeneity along the travers of the rover. Since the mineral phases associations can be linked to different formation scenarios of the moon, these data provide valuable in-situ petrological information. The RAX measurements will also be compared with Raman data obtained in-situ on Mars and help to differentiate between Martian and non-Martian surface minerals on Phobos. Furthermore, RAX measurements will be compared with Raman measurements performed in Earth laboratories on the returned MMX samples for better interpretation of the data acquired.

To demonstrate the functionality of the RAX instrument after the launch and to monitor its performance, a Verification Target (VT) is part of the payload. The VT is placed in the field-of-view of the RAX instrument and can be measured during cruise until the Rover will separate from the MMX spacecraft for landing on Phobos.

Figure 5 shows an image of the RAX instrument flight model.

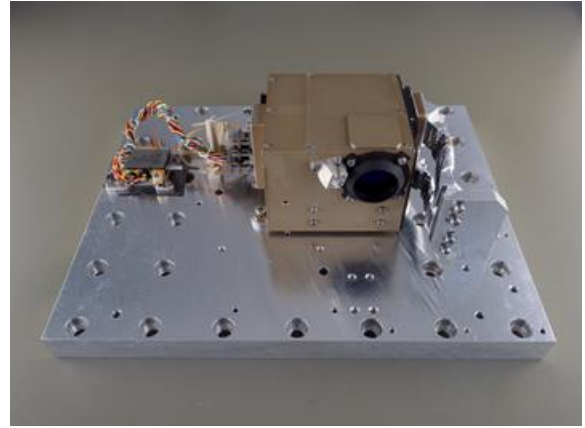


Figure 5: The RAX FM laser connected to the RAX FM spectrometer module (RSM). [15]

2.4 Radiometer, miniRAD

By measuring the surface temperature during day-night cycles, miniRAD will allow the surface thermo-physical properties of Phobos to be determined by measuring the radiative flux emitted in the thermal infrared wavelength range [17]. MiniRad will use thermopile sensors to measure flux in six wavelength bands and obtain information on regolith [18,19] and boulder [20] thermo-physical properties.

The instrument has strong heritage from the MASCOT radiometer MARA [21]. An image of the protoflight model sensor head is shown in Figure 6.

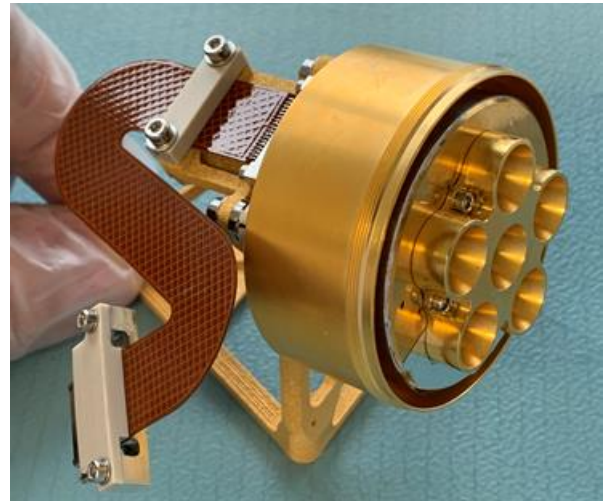


Figure 6: Protoflight model (PFM) of the miniRAD sensor head including the mounting bracket and showing the six apertures of the individual IR-channels as well as the flex harness connecting the sensor head to the miniRAD electronics.

3. System Overview and Operations

The rover has an allocated mass of 29,1 kg, (including the Mechanical Electrical Communication and Separation Subsystem (MECSS) and the communications system, which will stay on the main spacecraft) is based on a carbon fibre structure, a locomotion system with four individually controlled wheels and a power system with a solar generator and re-chargeable batteries.

The rover system is described in more detail e.g. in [3] and [4]. Figure 7 shows the Pre-Assembled Chassis (PAC), integrated at DLR in Bremen, shortly before delivery to CNES in Toulouse, where final integration takes place. Figure 8 shows the flight model of the Service Module (SEM), at CNES, including the internal structure supporting e.g. the cameras and RAX. Also central electronics and batteries are attached to the SEM.

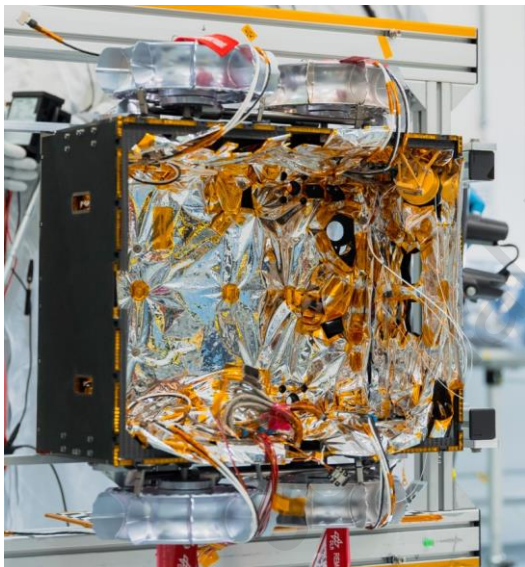


Figure 7: Protoflight model of pre-assembled chassis (PAC) including the locomotion system with the wheels (image: DLR).

In addition to the flight system, the overall system includes two ground segments (one in Germany and one in France). All communications between the rover ground segment and the flight segment is linked via the MMX spacecraft and the JAXA ground segment and ground stations.

Figure 9 illustrates the operations concept and communications strategy. A timeline of the MMX mission phases is given in [22].

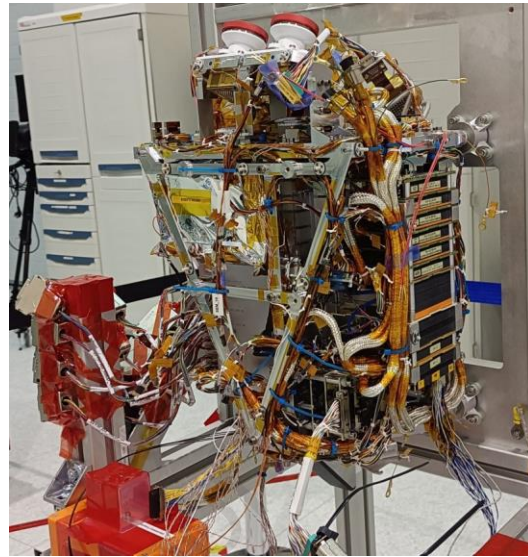


Figure 8: Protoflight model of service module (SEM). At the top, one can see the NavCams (image: CNES)

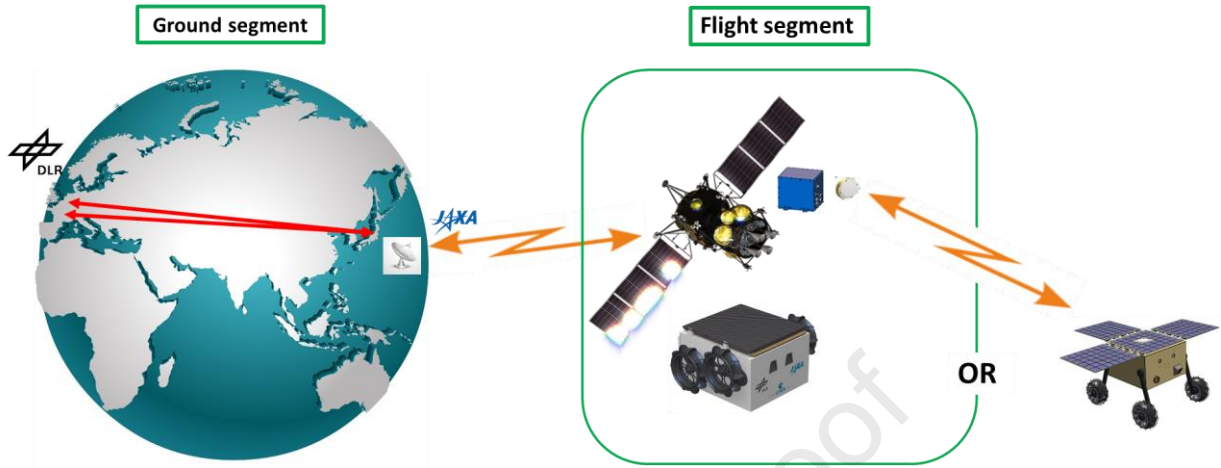


Figure 9: Operations concept and TMTC links for rover attached to main spacecraft or separated and on the surface of Phobos, respectively.

Integration and test of the rover system and its payload is divided between DLR (integration of chassis and locomotion system) and CNES (integration of internal module referred to as Service Module (SEM), and final AIT) Eventually, the complete rover flight model, attached to the MECSS, will be delivered to JAXA/MELCO to be integrated to the main spacecraft and undergo acceptance and functional tests on MMX level. The MMX Rover key system features are described e.g. in [3] and [13].

The rover will be mounted to the -z-panel (“bottom side”, between landing legs) of the MMX spacecraft during all mission phases until separation [1]. The actual delivery is planned to take place in the course of the rehearsal for the first MMX landing [22]. Consequently, the rover landing site will be close to the first sampling site in northern latitudes ($<30^\circ$) at Phobos' far side to Mars. Care is being taken to keep a distance between Rover and sampling site in the 100m range, to avoid rover contamination by dust, moved by the MMX propulsion system during the landing maneuver.

After separation from the main spacecraft at an altitude less than 45m, the rover will fall ballistically to the surface and impact it at a speed less than 0.9 m/s. It will come to rest after several uncontrolled bounces.

The rover will then up-right itself using the locomotion system and deploy the solar generator. All this needs to take place fully autonomously.

As soon as the rover is positioned upright with the solar generator deployed it is possible to analyse the

landing and send commands. Science operations can start.

4. Conclusions

The rover after passing its CDR is currently going through integration and qualification. The delivery of the flight model to JAXA is scheduled for summer 2023. The MMX mission will be launched in 2024.

Rover delivery to the surface of Phobos is planned for 2027. The data obtained will significantly enhance the science return of the overall MMX mission.

It is currently planned that MMX will leave Mars orbit in 2028 and return to Earth in August 2029 [1,22].

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- In this paper we give an overview of the rover, which will be part of the MMX mission to Phobos
- The MMX rover will explore the surface of Phobos with cameras, a Raman spectrometer and a radiometer
- Scientific objectives and the mission outline are discussed

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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