

SURFACE STRUCTURE AND PHOTONIC NANOARCHITECTURES IN SCALES OF WEEVILS

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Natural photonic nanoarchitectures in scales of weevils widely distributed in Europe have been acknowledged for the first time. A multi-level structure has been observed - the first level microstructure on the surface of the scales, the second level nanostructure on the surface of scales as well as internal photonic nanoarchitecture of scales. The overall colouration of scales is provided by the overlap of the optical effects created by these structures. There is some debate about origin and reasons of such complicated structure.

Key words: structural color, photonic nanoarchitectures, weevil, Coleoptera, Curculionidae.

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INTRODUCTION

Structural colours of animals are being researched for a long time, these phenomena have been studied also by such outstanding scholars as Hooke (1961), Newton (1952) and Rayleigh (1923). Recently, the interest concerning the structural colours of animals have increased considerably, since in animals and plants there have been discovered nanostructures of various kinds and the so-called photonics crystals (Yablonovitch 1987) in biological material (Biro et al. 2003), therefore there are numerous new publications in this field nowadays. Photonic crystals (PhCs), or photonic band gap (PBG) materials in physics and material sciences have been known for only twenty years, since the research carried out by Yablonovitch (1987) and John (1987). These are regular structures with a

periodicity in the order of the wavelength of visible light (Joannopoulos 2008). In wildlife, structures of this kind have been existing for billions of years. One-dimensional photonic crystals consist of parallel thin film layers of alternating high and low refractive index materials, i.e. the multi-layers. Multi-layers provide for the metallic and polarized colouration of, for example, the skin of cephalopods (Mathger & Hanlon 2007) and fishes (Mathger et al. 2003), the elytra of jewel beetles (Stavenga et al. 2011b, Hariyama et al. 2005, Mason 1927, Durrer & Villiger 1972), scarabs (Sharma et al. 2009, Brady & Cummings 2010), and the breast feathers of birds of paradise (Stavenga et al., 2011a). Two-dimensional photonic crystals, that is, structures with periodicity in two dimensions, underlie the coloration of peacock feathers (Zi et al. 2003, Loyau et al. 2007). Three dimensional

photonic crystals have been found in butterflies (Michielsen & Stavenga 2008, Poladian et al. 2009, Saranathan et al. 2010, Saba et al. 2011, Shawkey et al. 2009), as well as in the scales of many weevils and beetles (Wilts et al. 2012a, b, Parker et al. 2003, Wilts et al. 2012a, Galusha et al. 2008, Welch et al. 2007). Quasi-ordered three-dimensional photonic crystal structures, which manifest periodicity in all three dimensions, although imperfect, have been identified in bird feathers (Dong et al. 2010) and in the scales of some coleopterans (Morrone 2002).

The rapid development of nanoscience and nanotechnologies, as well as the interaction of physics and material science with biology has enhanced scholars' interest in natural nanostructures and photonic nanoarchitectures. The motivation of the industry is the possibilities to manufacture products that possess new and

significant qualities (Lenau & Barfoed 2008).

The research on animals' iridescence is interesting from the perspective of both biology and physics and material science. Lately the researchers have developed understanding of animals' communication strategies, where animals' coloration is of great significance. The development is in progress also bionics - the application of the nature's "inventions" in engineering and technology. One of the reasons underlying the great interest in this area is the possibility of "copying" brightness and metallic nature of animal colours in eco-friendly way. Imitation of natural iridescent structures is applicable also in holographic technologies.

The recent research shows that species of Curculionidae family can possess structures of

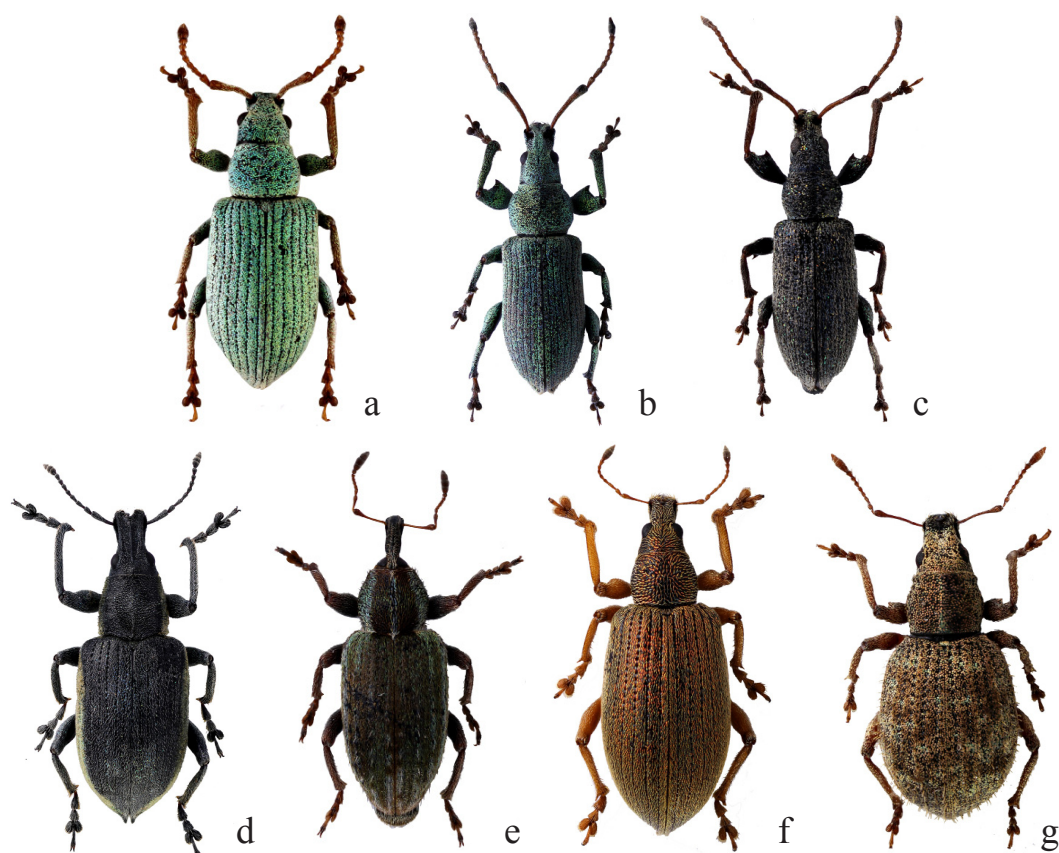


Fig. 1. Weevils a) *Phyllobius virideaeris*, b) *Phyllobius maculicornis* c) *Phyllobius argentatus* d) *Chlorophanus viridis*, e) *Hypera nigrirostris*, f) *Polydrusus mollis* g) *Sciaphilus asperatus*.

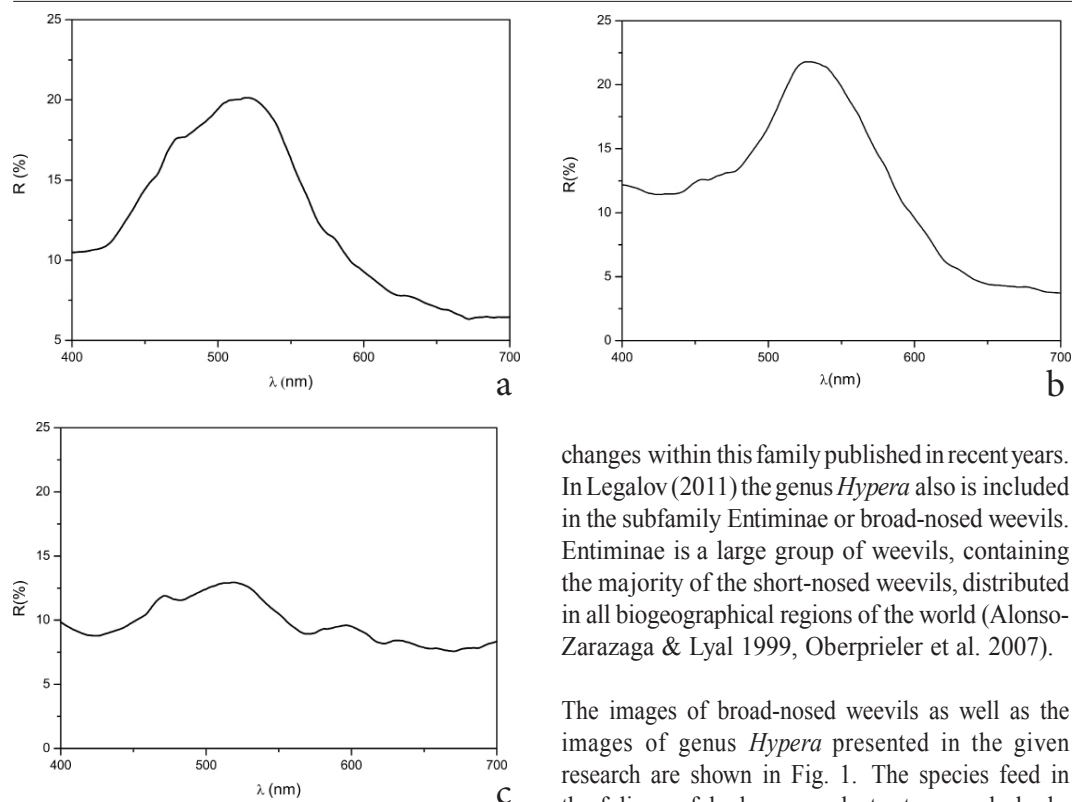


Fig. 2. Reflected spectras from scales of a) *Phyllobius virideaeris*, b) *Phyllobius maculicornis*, c) *Polydrusus mollis*.

photonic crystals, which generate specific colour effects in reflected light (Simonis & Vigneron 2011). However, by now most of investigations on photonic crystals of weevils have been carried out with exotic species (*Entimus imperialis*, *Pachyrrhynchus congestus*, *Lamprocyphus augustus*) mainly from tropical regions.

The species of weevils selected for this research belongs to the family Curculionidae Latreille, 1802. In this article, we follow the systematics suggested by Bouchard et al. (2011). According to the systematic, our research objects belong to the subfamily Entiminae Schnherr, 1823, genus *Chlorophanus* Sahlberg, 1823, *Phyllobius* Germar, 1824, *Polydrusus* Germar, 1817 and *Sciaphilus* Schnherr, 1823, as well as subfamily Hyperinae Marseul, 1863, genus *Hypera* Germar, 1817. The systematics of this beetle's family is complicated: there have been several articles on the taxonomic

changes within this family published in recent years. In Legalov (2011) the genus *Hypera* also is included in the subfamily Entiminae or broad-nosed weevils. Entiminae is a large group of weevils, containing the majority of the short-nosed weevils, distributed in all biogeographical regions of the world (Alonso-Zarazaga & Lyal 1999, Oberprieler et al. 2007).

The images of broad-nosed weevils as well as the images of genus *Hypera* presented in the given research are shown in Fig. 1. The species feed in the foliage of herbaceous plants, trees and shrubs (Balalaikins 2011, 2012a,b,c).

The upper surface of all beetles presented in our research is completely or almost completely covered with scales. Sometimes also femora and tibiae are covered with scales. The scales of different species of weevils are different in shape: from very thin ones, which are bifid up to the base (*Hypera nigrirostris*) to oblong, or oval. The scales are of various coloration: from greenish-blue to coppery and brownish, often with metallic shine. Recent research shows that this effect in true weevil species is caused by the structures of photonic crystals, which generate specific colour effects in reflected light (Simonis & Vigneron 2011).

The shape of scales, coloration and their position on the beetles' surface forms a set of features which are used for the identification of the beetles. Some authors propose to use a fine structure of the scales, which is obtained using a scanning electron microscope with a magnification of 1,500x, for beetle's identification (Erbey & Candan 2013).

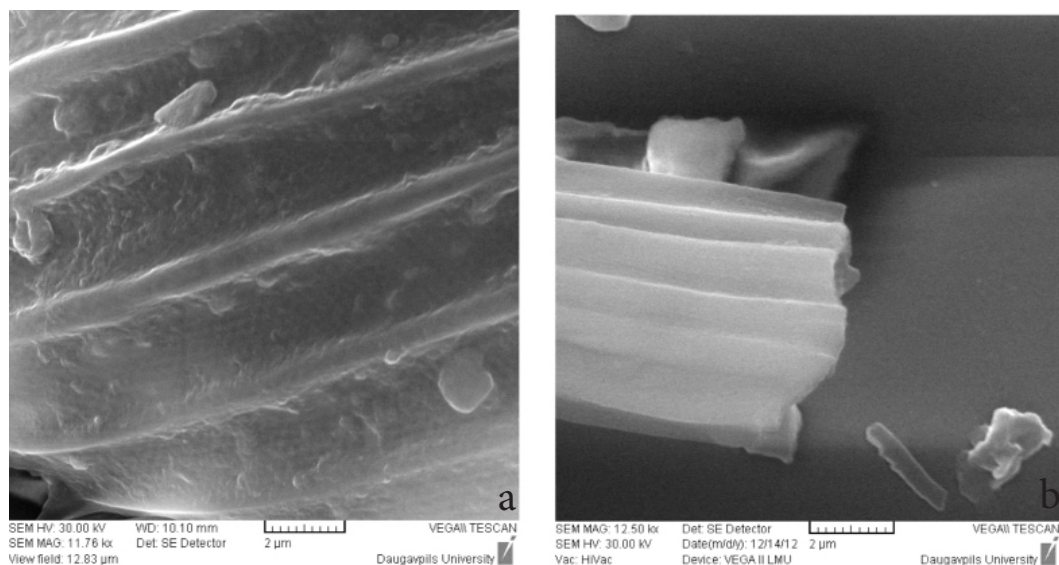


Fig. 3: Corrugation of the surface of scales a) *Phyllobius virideaeris*, b) *Chlorophanus viridis*.

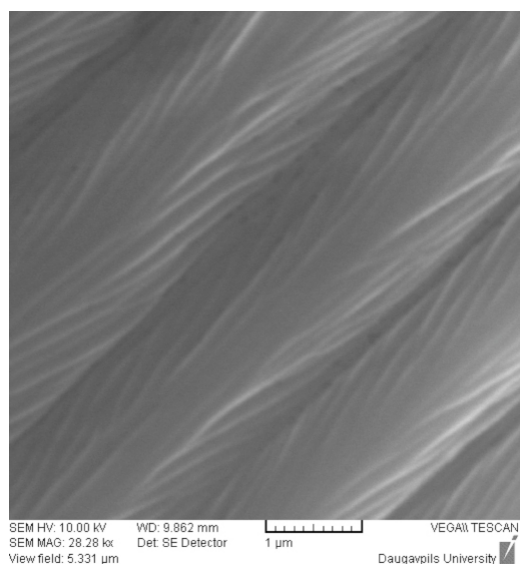


Fig. 4. Second order surface structure of scales of *Phyllobius maculicornis*.

MATERIAL AND METHODS

Dried specimens were obtained from the collection of the Institute of Life Sciences and Technology (Daugavpils University, Latvia). The photographs of habitus were taken using a Nikon SMZ 745T stereomicroscope and a Nikon Digital Sight DS-Fi1

digital camera. The research of material structure was realized by the electron scanning microscope Vega II LMU (Tescan), samples were coated by 10 nm Ag coating. Spectroscopic investigations were done by microspectrophotometer MSP500 (Angstrom Sun Technologies). Reflected spectra were obtained from elytral scales of beetles with well-expressed reflective characteristics.

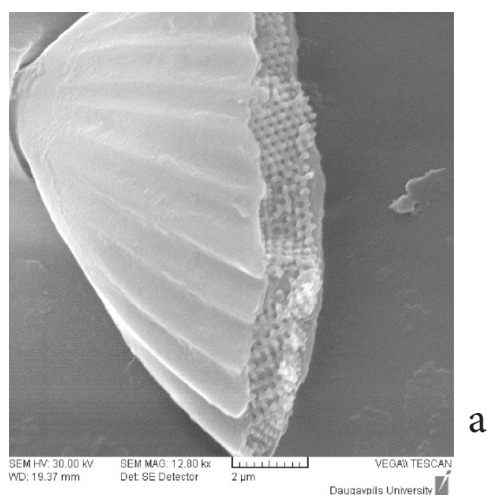


Fig. 5. Fonic nanoarchitectures of scales a) *Phyllobius virideaeris*.

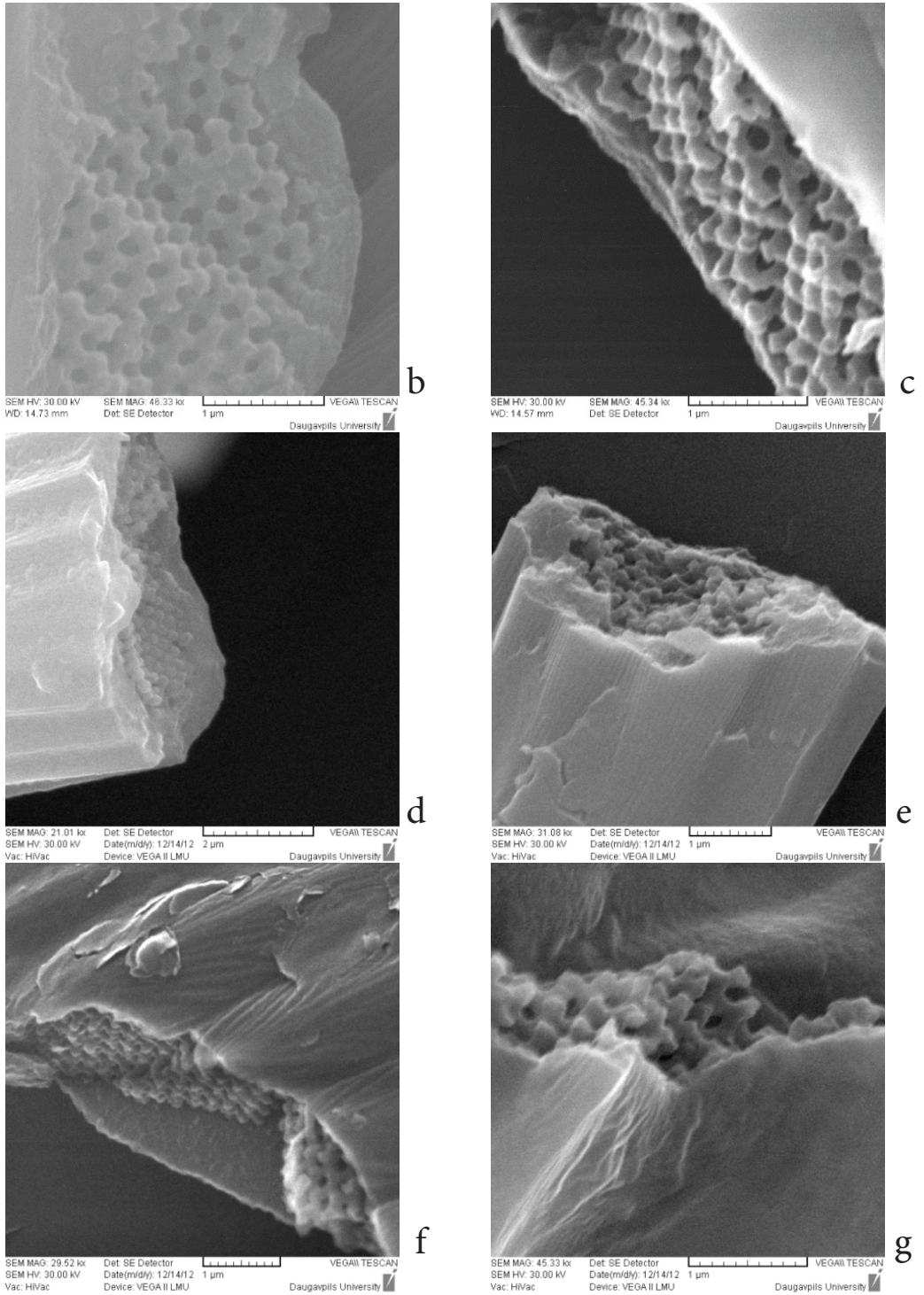


Fig. 5. Photonic nanoarchitectures of scales b) *Phyllobius maculicornis*, c) *Polydrusus mollis*, d) *Chlorophanus viridis*, e) *Hypera nigrirostris*, f) *Phyllobius argentatus*, g) *Sciaphilus asperatus*.

RESULTS

In some insects, the reflected spectra obtained during the research are represented in Fig. 2. The maximums of the reflected colour observed correspond to the primary colour of the insects. The reflected light observed has metallic shine and manifests iridescence - the observation angle being changed, the coloration slightly changes. Besides, some insects (*Chlorophanus viridis*, *Phyllobius argentatus*) have scales of two different types - round and oblong, they have different coloration.

In all the insects the surface of scales manifests corrugation with the intervals of approximately 1 to 2 micrometres (see some examples in Fig. 3), which is the cause of the effect of colour iridescence, as it corresponds to the diffraction grating.

In the same vein, in all the insects analyzed the second level (secondary) structure has been observed on the surface of scales: nanostructural riffling - approximately 100 nm in width, some micrometres in length with the period of approximately 200 nm. Especially well expressed this structure is in the scales of *Phyllobius maculicornis* (Fig. 4). It is clear, that quasi-ordered scattering (Seago et al. 2009) determined by the internal structural architecture of scale-like structures is responsible for the dominant colour of the reflected light. The structural nanoarchitecture is illustrated in Fig. 5 - lattice with different period, this period is what determines the dominant wavelength of the reflected light.

DISCUSSION

The second-order structure (Fig. 4) is necessary for ensuring of the clean liness of the surface of a beetle's scales, because waxy nanostructures can ensure self-cleaning property of surface - the so-called "lotus effect" (Furstner et al. 2005). Nanostructuring of surface increases its hydrophobic characteristics as well (Byun et al. 209). There are a number of cases when the primary function of micro- and nanostructural

formations in insects is friction-reducing or water-repelling (Seago et al. 2009).

The photonic nanoarchitectures observed within the framework of the present research are similar to the structures observed by Welch et al. (2007) and can be attributed to inverse opal structure (Joannopoulos 2008). Although, in the case of *Chlorophanus viridis* the structure of oblong scales, which are located in the dorsal part, more resembles the spherules observed in other studies (see (Simonis & Vigneron 2011, Rassart et al. 2009)), moreover, the scales on the sides of this insect are of a different dominant colour, as well as a different structure - inverse opal that has been observed also in scales of the second (round) type. To present a thorough explanation of the mechanisms of development and the functions of such complicated structures, additional research is necessary.

CONCLUSIONS

The nanoarchitectures developed by chitin occurring in the beetle's individuals representing the species *Phyllobius virideaeris*, *Phyllobius maculicornis*, *Polydrusus mollis*, *Chlorophanus viridis*, *Hypera nigrirostris*, *Phyllobius argentatus* and *Sciaphilus asperatus* were investigated by means of electron scanning microscopy and reflectance spectroscopy. The multiple surface structure, as well as the photonic nanoarchitectures inside the scales were observed. We believe that the interaction of these structures altogether determines the ultimate colouration of the beetles. To date, photonic architectures have been observed mainly in exotic specimens, the present research proves that such complicated formations are widely distributed in nature - the conclusion can be drawn that, most probably, the nanostructures of this kind are typical of all the weevils. The research of these structures provide more information concerning their origin, as it is acknowledged also by Priscilla Simonis and Jean Pol Vigneron (Simonis & Vigneron, 2011).

The research of bionanostructures is interesting also for physicists and material scientists,

for example, as samples for creating new nanoarchitectures or new photonic materials, iridescent lattices can be worthwhile for development of holograms with reproduction of natural structures and iridescence effects.

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