Seasonal Variation in the Abundance of the Demersal Copepod *Pseudodiaptomus* sp. (Calanoida, Pseudodiaptomidae) in the Seomjin River Estuary, Southern Korea

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Abstract - We conducted a year-long survey in 2000 to examine seasonal fluctuations in the abundance of the demersal copepod *Pseudodiaptomus* sp., the dominant copepod in the Seomjin River estuary, where the spring tide strongly affects changes in salinity gradients. *Pseudodiaptomus* sp. was found throughout the year in the entire range of salinities measured, but most individuals appeared at oligohaline conditions below 5.0 psu, and less than 2% were observed in polyhaline conditions above 18.0 psu. The peak abundance occurred during autumn in oligohaline waters, and the density was relatively low during the rainy season in summer. In spring and autumn, copepodites were most abundant in oligohaline waters, although they were also fairly abundant in mesohaline conditions (5 ~ 18 psu). Females with egg sacs appeared in oligo- and mesohaline waters during spring and autumn but were seldom found in polyhaline conditions throughout the year. Our results indicate that, despite the strong physical influence of the tide, *Pseudodiaptomus* sp. can manipulate its position to remain at its preferred salinity. We also found that spawning mainly occurred in oligohaline waters twice a year.

Key words : Seomjin River estuary, *Pseudodiaptomus* sp., seasonal variation, salinity gradient, temperature, Chlorophyll-*a* concentration

INTRODUCTION

As the power of locomotion is relatively weak in zooplankton and as the organisms respond passively to the flow of currents and tides, the distribution of zooplankton is fully dependent on such physical flows. Nevertheless, different species of zooplankton require unique environmental conditions for reproductive activities. Salinity is thought to be the most important among these conditions, as it influences water temperature and osmoregulation, which determine the metabolic rates of the organisms (Barlow 1955; Lance 1963). In addition, the environmental conditions required for reproductive activities are much more complicated than the habitat conditions. Thus, even if species are adapted to an area with highly variable salinity, such as an estuary, the range of salinity fit for reproduction differs by species (Collins and Williams 1981).

Several reports have indicated that, despite their weak power of locomotion, some species of zooplankton that occur in estuaries can actively cope with transportation by the tide and can remain at their preferred salinity concentrations (Cronin *et al.* 1962; Wooldridge and Erasmus 1980; Collins and Williams 1981; Hough and Naylor 1991; Kimmerer *et al.* 1998). Moreover, other reports have indicated that the pattern of appearance of species in estuaries is related not only to salinity but also to temperature, food, turbidity, tides and other factors (Castel and Veiga 1990; Jerling and Wooldridge 1991; Laprise and Dodson 1994; Liang and Uye 1997a, b).

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Pseudodiaptomus sp. is so dominant in the Seomjin River estuary in Korea that it comprises over 20% of zooplankton in the area (Park *et al.*, unpublished data). In this study, we investigated the distribution and the spawning season of *Pseudodiaptomus* sp. based on seasonal changes in salinity.

MATERIALS AND METHODS

The Seomjin River located in the Jellanam-do of Korea is 226 km long and the ninth-longest river, the area of its basin is 4,897 km^2, and annual average rainfall is 1,253 mm, with over 70% concentrated in summer. Water depth in the estuary averages 7~8 m with a maximum of 15 m at station 5 (see Fig. 1). The largest tide range is 4.5 m, so fresh water is well mixed with sea water. Zooplanktons were collected monthly in 2000 at six stations between Seomjin Village (35° 05′N), where salinity is nearly 0 psu, and Gwangyang Bridge (34° 40′N), where salinity is >25.0 psu. Each station was established based on intervals of approximately 5.0 psu, and zooplankton samples were obliquely towed for 5 min using a NORPAC net (mouth diameter: 45 cm, mesh size: 200 μm) fitted with a Rogosha flow meter at a speed of 2.5 knots from the bottom layer to the surface layer (Fig. 1). Sampling was completed in 3 h, beginning at station 1 on each occasion. Water temperature and salinity were measured using a T-S meter (YSI, Model 30) from the surface layer to the bottom layer at intervals of 1 m. To measure chlorophyll *a* concentration, 1,000 mL of water was collected from the surface layer of each fixed station. The collected sea water was filtered through glass-fibre filter paper (Whatman GF/F) using a vacuum pump; for the analysis, pigment was extracted by grinding the filter paper in a dark room and placing it in 90% acetone as recommended by SCOR-UNESCO (1980). The extracted sample was centrifuged, and the absorbance (at 750, 664, 647, and 630 nm) of the supernatant was measured with a spectrophotometer (UNICAM Helios *a*). The Seomjin River estuary was divided into oligohaline (0~5 psu), mesohaline (5~18 psu), and polyhaline (>18 psu) regions according to Ekman's classification system (Day *et al.* 1989). The abundance of *Pseudodiaptomus* sp. was expressed as individuals per cubic meter (indiv.m^{-3}).

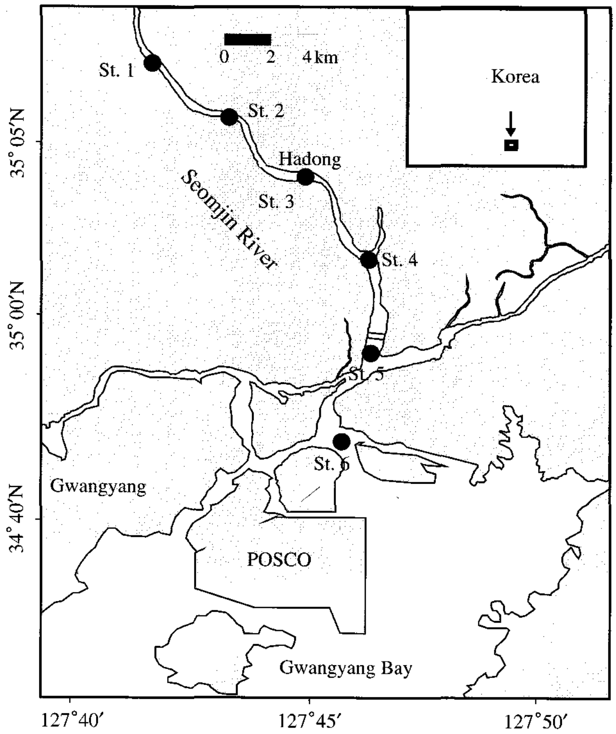

Fig. 1. Sampling stations in the Seomjin River estuary, southern Korea.

RESULTS

Environmental factors

Water temperature

The water temperature measured during the research period ranged from 0.6~27.5°C, with the lowest temperature recorded in January and the highest in July (Fig. 2a). In spring, differences in water temperature among the fixed stations were less than 1°C and were around 0.2°C between the surface layer and the bottom layer. In summer, however, the differences in water temperature among the fixed stations, as well as between the surface and the bottom layers, were approximately 2°C. In autumn, the differences in water temperature among the fixed stations were approximately 3°C, although the difference between station 1 and station 6 was as great as 6°C. In September, however, the differences in water temperature among the fixed stations were similar to those in summer. The difference in water temperature between the surface layer and the bottom layer was less than 0.5°C in October but as great as 5°C in November. The differences in water temperature among the fixed stations were approximately 2°C during winter, sim-

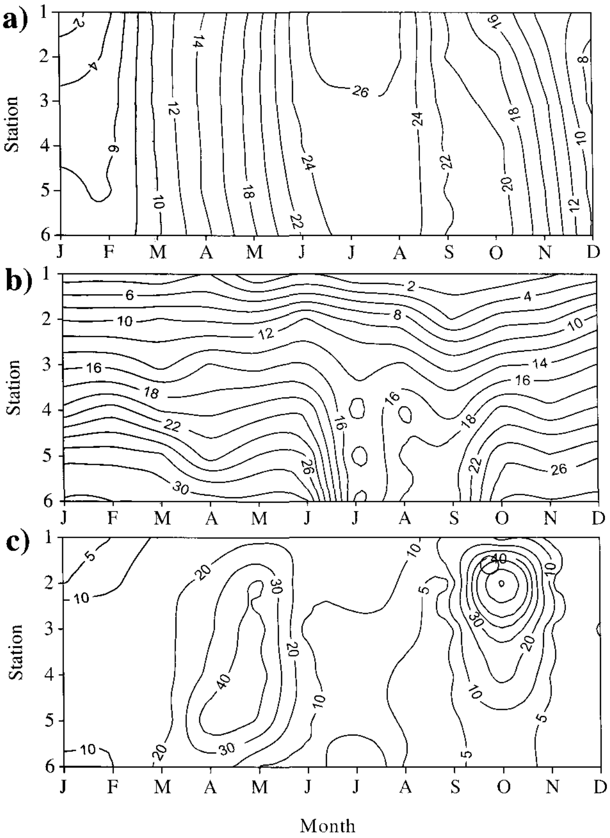

Fig. 2. Monthly spatial and temporal variations in the water temperature, salinity, and chlorophyll-*a* concentration in the Seomjin River estuary: (a) temperature (°C); (b) salinity; and (c) chlorophyll-*a* (μg L^{-1}).

ilar to the differences observed in the summer, whereas the difference between stations 1 and 6 was as great as 6°C in January. In addition, the difference in water temperature between the surface layer and the bottom layer was approximately 2°C.

Salinity

Salinity measured during the research period ranged from 0.0~32.2 psu, and clear differences in the distribution pattern were observed among seasons and among the fixed stations (Fig. 2b). Station 1 showed salinity below 5.0 psu throughout the year, and the difference between the surface layer and the bottom layer was around 0.2 psu. Stations 2 and 3 showed salinity values from 7.0~10.2 psu and 11.1~16.3 psu, respectively, throughout the year; at these two stations, the differences between the surface layer and the bottom layer were around 1 psu. Station 4 varied in salinity between 14.7 and 20.5 psu, and the differences in salinity between the surface layer and the bottom layer were 1.0 psu in spring and winter and >5.0 psu in summer and autumn. Salinity at stations 5 and 6 exceeded 25.0 psu throughout most of the year, although it was below 18.0 psu in July, August and September owing to the influence of rainfall. In addition, the differences in salinity between the surface layer and the bottom layer at stations 5 and 6 were on average 5.0 psu, although this difference was as large as 10.0 psu in summer.

Chlorophyll *a* concentration

The chlorophyll *a* concentration measured during the research period ranged from 2.5~108.9 μg L^{-1} and differed by season and station (Fig. 2c). At station 1, which was oligohaline, the chlorophyll a concentration was 2.5~18.2 μg L^{-1} throughout the year, with the highest value in July and the lowest in November. At station 2 (mesohaline), the chlorophyll *a* concentration was 3.7~108.9 μg L^{-1}, with the highest value in October (108.9 μg L^{-1}) and the second highest in May (43.1 μg L^{-1}). In addition, stations 3 and 4 (mesohaline) showed high chlorophyll *a* concentrations (3.0~44.4 μg L^{-1} and 3.8~45.2 μg L^{-1}, respectively), although here, the concentrations were highest in May. At stations 5 and 6, the concentrations were 2.5~48.5 μg L^{-1} and 2.8~23.7 μg L^{-1}, respectively, with the highest value recorded in April and the lowest in December.

Distribution pattern of *Pseudodiaptomus* sp.

Pseudodiaptomus sp. appeared in the entire range of salinities in the Seomjin River estuary and throughout the year. Most individuals were found in oligohaline waters, but a relatively high abundance also occurred in mesohaline waters (Fig. 3). The density in polyhaline waters was very low, <2%. The adult density was as high as 3,561 ind m^{-3} on average in oligohaline waters in spring, but only 101 indiv.m^{-3} and 9 indiv.m^{-3}, respectively, in June and August and <1 indiv.m^{-3} in July, which included the rainy season. However, the density increased and reached its peak (90,240 indiv.m^{-3}) in October, after which the abundance decreased again (Fig. 4a). The abundance in mesohaline waters also increased in spring and autumn but was somewhat lower than that in oligohaline waters. Copepodites reached their peak abundance in oligohaline waters mainly in spring and autumn (Fig. 4b).

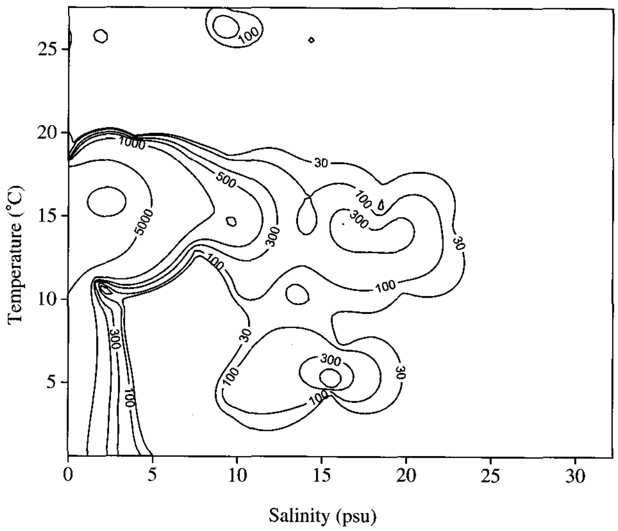

Fig. 3. Abundance-temperature-salinity diagram for *Pseudodiaptomus* sp.

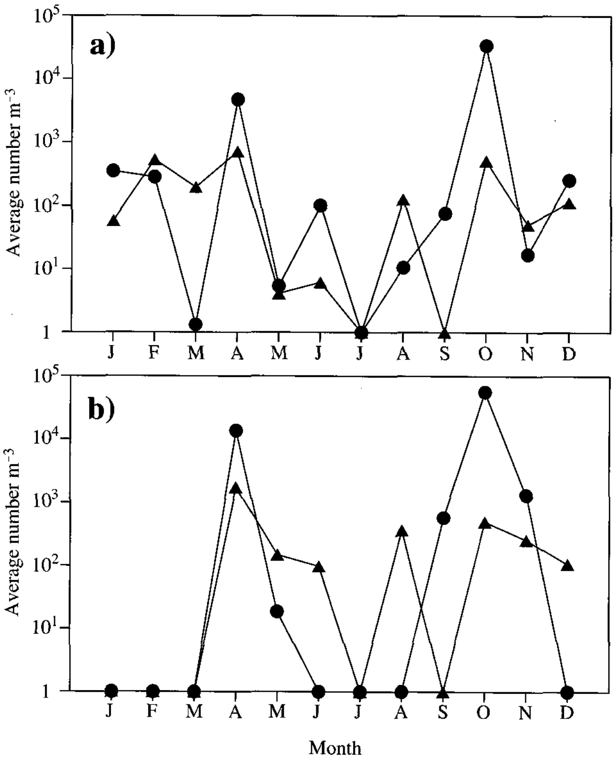

Fig. 4. Seasonal variation in abundance (ind m^{-3}) of (a) adults and (b) copepodites of *Pseudodiaptomus* sp.; circles: oligohaline, triangles: mesohaline.

Ratio of male to female *Pseudodiaptomus* sp.

Males were twice as abundant as females in spring to autumn, except in July and September (Fig. 5). In March,

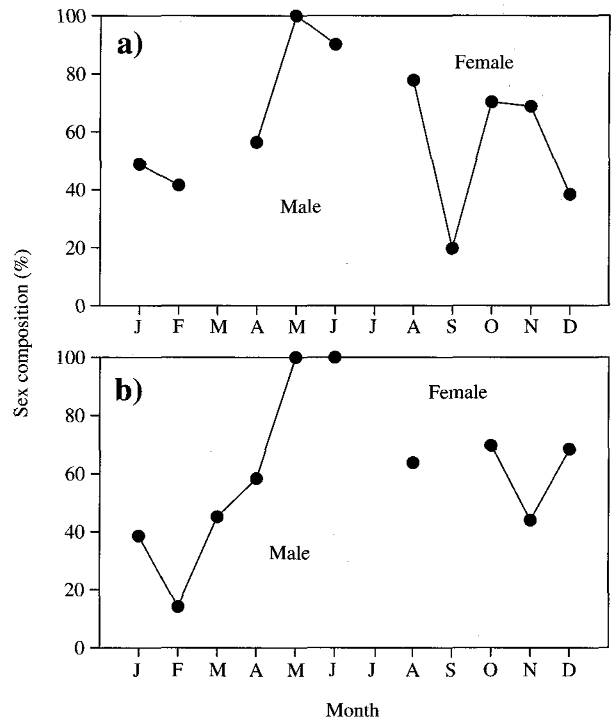

Fig. 5. Ratio of male to female *Pseudodiaptomus* sp.: a) oligohaline, b) mesohaline.

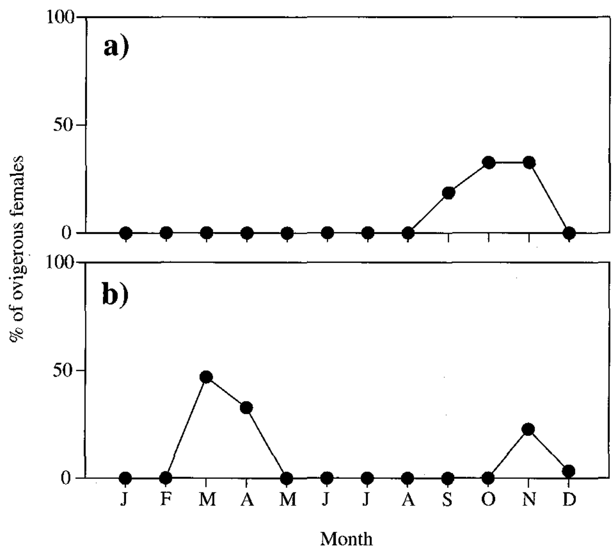

Fig. 6. Seasonal variation in the composition of ovigerous females of *Pseudodiaptomus* sp.; a) oligohaline, b) mesohaline.

neither males nor females appeared in oligohaline waters, whereas male and female densities in mesohaline waters were 89 indiv.m^{-3} and 74 indiv.m^{-3}, respectively. In September, both males and females appeared in oligohaline waters; in December, the abundance of females was higher

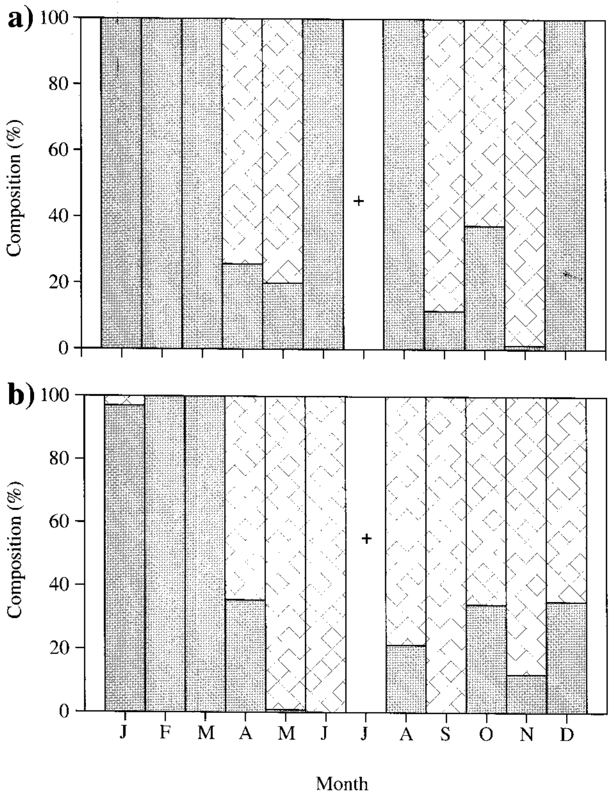

Fig. 7. Seasonal variation in the composition of adults (black bars) and copepodites (hatched bars) of *Pseudodiaptomus* sp.; a) oligohaline, b) mesohaline. + indicates that *Pseudodiaptomus* sp. was not found within the study areas.

than that of males in oligohaline waters but lower in mesohaline waters. Females with egg sacs appeared in oligohaline waters only during autumn (30% on average), but they did not appear in other seasons (Fig. 6a). Females with egg sacs appeared in mesohaline waters in spring and in November (Fig. 6b). In December, when the chlorophyll concentration was highest, females with egg sacs appeared only in mesohaline waters (around 3%), and almost no females with egg sags appeared in polyhaline waters throughout the year. In oligohaline waters, the ratio of copepodites to adults was >62% in spring and autumn, but no copepodites were found in summer and winter. However, in mesohaline waters, the ratio of copepodites to adults was >65% in all seasons except spring (Fig. 7).

DISCUSSION

Pseudodiaptomus sp. found in brackish and/or fresh waters of Korea has been reported as *P. inopinus* (Chang and Kim 1986; Suh *et al.* 1991; Kim *et al.* 2000). However, Soh *et al.* (2001) maintained that the latter may be found only in the brackish and/or fresh waters of western Korea, while the former dominates in the brackish waters of the southern and eastern Korea. A mitochondrial cytochrome oxydase subunit I sequences of *Pseudodiaptomus* sp. also differ from those of *P. inopinus* by 21.28% (in submitted in Hydrobiologia by Soh *et al.*). Considering that in other copepods such as *Calanus* species, interspecific mtDNA divergence ranged from 7.3 to 25.5% (Bucklin *et al.* 1995), the differences above mentioned are large enough for *Pseudodiaptomus* sp. to be classified as a separate, valid species.

Pseudodiaptomus sp. appears throughout the year at salinities below 18.0 psu in the Seomjin River estuary located in southern Korea. The peak abundance was observed in oligohaline waters in spring and autumn at water temperatures ranging from 10 to 20°C, whereas, in summer and winter, its density was quite low (Fig. 5). On the other hand, *P. inopinus* is in a range of 2.1 to 30.8°C and euryhaline (0.7 ~ 26.6 psu), but it shows high abundance at water temperatures below 8.9°C, except for one case observed at 28.0°C (Uye *et al.* 2000). Such differences in the spatio-temporal occurrence patterns suggest that *Pseudodiaptomus* sp. is ecologically different from *P. inopinus*.

Species inhabiting brackish water zones with high variation in salinity appear to move vertically in response to transportation by tides, in order to remain at a preferred salinity (Hough and Naylor 1991; Kimmerer *et al.* 1998). Considering that *Pseudodiaptomus* sp. was found primarily in medium-salinity water below 18.0 psu, it appears that this species is able to remain in its preferred range of salinity. However, differences in abundance between the surface and the bottom layer were not significant ($p > 0.05$). This may be because the Seomjin River estuary is not very deep and the tide covers a large range; as a result, water in the surface layer is actively mixed with water in the bottom layer.

Pseudodiaptomus sp. was not observed during the rainy season in July, although its preferred salinity concentration was measured in all water zones surveyed. Only a few individuals were found in the surface layer (< 22.0 psu) of Gwangyang Bay, 2 km away from station 6 (Park *et al.* unpublished data). It is possible that the individuals were swept off by the turbulent current caused by the mass outflow of fresh water, or that the disappearance of a salinity concentration transition zone negatively affected the physiological functions of *Pseudodiaptomus* sp. As the variation in salinity became stabilized, the abundance of *Pseudodiaptomus* sp. began to increase mainly in mesohaline waters, and the peak abundance was observed in oligohaline waters during October when the chlorophyll *a* concentration was highest. This suggests that a heavy inflow of fresh water, such as a monsoon flood, is important for increasing the density of individuals in estuaries (Wooldridge and Melville-Smith 1979). On the other hand, Ueda *et al.* (2004) reported that a gorge connected to the estuary of the river is important in maintaining the population of copepod species that move from the estuary to the bottom layer of the gorge.

The distribution of species that inhabit estuaries is closely related not only to salinity but also to water temperature, food, and other factors (Uye *et al.* 1982). In the Seomjin River estuary, water temperatures in spring and autumn were similar, both being within the range of 10 to 20°C, but the chlorophyll *a* concentration was higher in autumn than in spring (Fig. 2). Moreover, the dominant phytoplankton that contained chlorophyll *a* was blue-green algae in spring and diatoms in autumn. Food quality may have important effects on the egg production and death rate of copepod species (Gasparini and Castel 1997). Engstrm *et al.* (2000) showed that the death rate increased, and the egg production and hatching rate decreased, in *Eurytemora affinis* that consumed toxic cyanobacteria. In the case of *Pseudodiaptomus* sp. in the Seomjin River estuary, adults appeared only in mesohaline waters during spring when cyanobacteria were dominant, but they appeared in both oligo- and mesohaline waters during autumn when diatoms were dominant. The ratio of immature copepods was also highest in mesohaline waters during spring. In contrast to many other copepod species in brackish waters that offer many food choices, *Pseudodiaptomus* sp. is omnivorous. Thus, we suggest that reproduction may be affected more by water temperature and salinity than by food, although the hatching rates of *Pseudodiaptomus* sp. were not examined.

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