Non-Contact Detection of Surface Quality of Knot Defects on Eucalypt Veneers by Near Infrared Spectroscopy Coupled with Soft Independent Modeling of Class Analogy

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A knot is a natural defect that degrades the quality of softwood and hardwood veneer. To improve efficiency, the plywood industry needs a rapid, inexpensive method of knot identification that is easy to operate and industrialize. Although a non-contact knot-detection technology based on NIR spectroscopy and soft independent modeling of class analogy (SIMCA) has been successful in detecting softwood knots, it has not yet been explored in eucalypt (hardwood) veneer. This study investigated the interaction between knot size, spectral pretreatment methods, and wavelength range selections on this model's classification accuracy of knots and normal eucalypt wood. The study found that classification results were accurate up to 94.4% for large knot samples (10 to 15 mm in diameter) and up to 100% for knot-free samples. Spectral data for small knots (< 5 mm in diameter) impeded the model's classification accuracy because of confusion between small knots and both large knots and normal wood. Calibration models developed with second-derivative spectra exhibited the highest accuracy, followed by models built with first-derivative spectra, models based on spectra transformed by vector normalization, and the model based on the raw spectroscopy. Wavelength ranges of 1100 to 2500 nm enabled greater classification accuracy than wavelength ranges of 780 to 1100 nm or 780 to 2500 nm.

Keywords: Non-contact detection; Knot defects; Eucalypt; Veneer; Near infrared spectroscopy; Soft independent modeling of class analogy (SIMCA)

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INTRODUCTION

Eucalypts, as a hardwood species, are one of the fastest growing woody plants in the world, with average annual growth rates up to 100 m^3ha^{-1}. In the past, eucalyptus wood was used primarily to produce low value-added fibers, pulp, and paper because of its superior fiber and pulping properties (Santos and Pinho 2004). As a result of increasing global demand for plywood and the shortage of wood resources, many researchers have studied the feasibility of using eucalyptus to produce plywood and laminated veneer lumber (LVL), finding that its strong physical and mechanical properties are sufficient to meet quality requirements (Sahin 1998).

Veneer quality plays a key role in the performance of plywood, LVL, and other laminated products. To control the product quality, manufactured veneers must first be separated into different quality grades, depending on the severity and distribution of surface defects. The surface defects affecting the quality of veneer include knots, decay, discoloration, cracks, and holes. As one of the most potentially significant defect, knots contain many extractives. Knots in softwoods have been found to contain polyphenols, such as lignans, oligolignans and stilbenes, while hardwood knots are rich in flavonoids (Holmbom *et al.* 2003; Valimaa *et al.* 2007). The presence of these extractives affects the movement of moisture, which can cause inhomogeneity during the drying process that leads to further warping and deformation (Hernandez 2007; Royer *et al.* 2010). Extractives also affect the permeability of veneer as well as its impregnation and dyeing. Softwood knots always exude a resin, which can influence the bonding quality and painting property of veneer. Knots can also affect the mechanical properties of veneer or laminated wood. Areas with knots are more dense and have a different direction of annual rings and materials than knot-free areas. Several mechanical properties that can be influenced by knots include stiffness (Todoroki *et al.* 2010), tensile strength (Takeda and Hashizume 1999; Takeda and Hashizume 2000), bending strength (Frank *et al.* 2005), and bending modulus of elasticity (Zhong *et al.* 2012).

The traditional method of knot detection is performed by a human inspector, but its efficiency and accuracy is low due to eye fatigue. Thus, there is significant interest among plywood and LVL manufacturers in developing accurate methods that can be used to identify knots in the surface of veneer. Currently, several new techniques exist to replace human inspectors. Microwave detection technology, based on the change in amplitude and phase of electromagnetic waves in the area with knots, can reliably detect knots (Baradit *et al.* 2004; Baradit *et al.* 2006). The direction of annual rings and materials in the area with knots is different from surrounding areas, which would affect the ultrasonic wave velocity through wood (Karsulovic *et al.* 2000). Based on this principle, ultrasonic methods have been advanced as one way to detect knots (Kodama and Akishika 1993; Kabir *et al.* 2003). Additional work has been performed using non-destructive knot identification techniques, such as acoustic waves (Wang *et al.* 2003), X-rays (Cristhian *et al.* 2008), laser scattering based on tracheid effects (Törmänen and Mäkynen 2009), and near infrared (NIR) spectroscopy for wood stiffness (Meder *et al.* 2002).

To improve work efficiency, the plywood industry needs a rapid and inexpensive method of knot identification that is easy to operate and industrialize. Near infrared (NIR) spectroscopy, as a nondestructive detection and identification technology developed over the past 20 years, has the potential to meet these requirements. NIR spectroscopy has been widely used for the evaluation of wood density (Stirling *et al.* 2007), wood grain-angle (Gindl and Teischinger 2002), wood chemical composition (Zahri *et al.* 2008), and veneer MOE (Meder *et al.* 2002). It has also been applied in the detection of wood defects, such as discriminating blue-stained wood (Via *et al.* 2006; Via *et al.* 2008), distinguishing the type of fungal decay (Fackler *et al.* 2007; Yang *et al.* 2008), and detecting compression wood (Meder and Meglen 2012). Compared to normal wood, knots have different colors, densities, grain angles, and chemical compositions, all of which can be predicted by NIR spectroscopy coupled with chemometrics. Thus, it is feasible to detect knots in veneers from clear wood using NIR.

Soft independent modeling of class analogy (SIMCA) is one of common multivariate data analysis techniques. Using SIMCA, unknown samples can be classified based on the model of principal component analysis (PCA) (Wold 1976). Many researchers have demonstrated that SIMCA classification based on NIR spectroscopy has high accuracy and significant efficiency (Woo *et al.* 2002). It is worth noting that Fujimoto and Tsuchikawa (2010) have studied the identification of dead and sound knots on wood surfaces using NIR spectroscopy coupled with SIMCA, but only Japanese larch boards were used in their research.

Previous research investigated the feasibility of using NIR spectroscopy and SIMCA to detect knots in softwood Masson pine veneers (Yang *et al.* 2009). Results indicated that the discriminant accuracy of SIMCA models for raw spectra, first-derivative spectra, and second-derivative spectra of samples with or without knots was greater than or equal to 90%. In the present study, eucalypt wood, as a hardwood, was selected to complement the softwood results in the work referenced above. Spectroscopic data from the knotted and knot-free area on eucalypt veneer were analyzed to evaluate the ability of NIR spectroscopy in combination with SIMCA to assess knots and normal wood. These data were also analyzed to ascertain their classification accuracy according to different knots size, spectral pretreatment methods, and wavelength regions, thereby helping to determine the most effective method of measurement and analysis.

EXPERIMENTAL

Ten eucalypt (*Eucalyptus urophylla* × *E. grandis*) trees were collected from the Leizhou forestry bureau in Guangdong province, China (20°18′ to 21°30′, 109°39′ to 110°38′). The logs were peeled into veneers with dimensions of 2000 mm × 1300 mm × 1.7 mm. The veneers were air-dried to approximately 6% moisture content. For more convenient measurement, the air-dried eucalypt veneers were cut into smaller size veneers of 400 mm × 200 mm × 1.7 mm. Eucalypt veneers with live knots on the surface were sorted out and divided into two categories according to their sizes: small knots (less than 5 mm in diameter) and large knots (10 to 15 mm in diameter). This provided three types of samples: knot-free veneers, veneers with small live knots, and veneers with large live knots. Table 1 summarizes the number of samples for the calibration and test sets at different species and different knot types. A total of 174 samples from eucalypt veneers with a moisture content of approximately 6% were prepared for analysis.

NIR diffuse-reflectance spectra were collected using a Field Spec® NIR spectrometer (Boulder, CO, USA) provided by Analytical Spectral Devices (ASD) at a spectral resolution of 1 nm between 350 and 2500 nm, with an integration time of 100 ms. A fiber optic probe was oriented perpendicular to the sample surface and used to collect spectra. The spot diameter was 18 mm with a halogen bulb lightsource. Power requirements were 12 to 18 VDC, 6.5 W. A piece of commercial polytetrafluoroethylene (PTFE) panel was used as the white reference material. For each sample, six scanning points were selected, each of which received on average 30 individual scans to comprise a single sample spectrum. The mean of spectrum from these six scanning points per sample was used for statistical analysis. All spectroscopy measurements were made in a controlled humidity chamber (50 to 60%) and at 20 ± 2 ºC.

Unscrambler v9.2 (CAMO, Corvallis, OR, USA) software was employed for data pretreatment, PCA computing, and SIMCA analysis. In addition to raw spectra and vector normalization spectra, a first-derivative polynomial with 17 smoothing points (Savitzky and Golay 1987) and a second-order polynomial were utilized to develop the classification models. The samples were divided into a calibration set and a validation set. About two-thirds of the specimens were used in the calibration set, and one-third were used for random validation (Table 1). Prior to SIMCA classification, a separate principal component analysis (PCA) model for each type was built. PCA is a multivariate method that can estimate the correlation structure of the variables. It can reduce the dimensionality of the original variables according to the importance of a variable in a PC model (Wold *et al.* 1987).

SIMCA was used to classify unknown samples by comparing the distance between unknown samples and the already existing PCA models. An F-test for statistical significance was used for the model validation at a significance level of 0.05. Model distance can also be used to evaluate the classification model. As a rule of thumb, two models are almost identical if the model distance is close to 1, while models have a significant difference if the models' distance is greater than 3 (Esbensen *et al.* 2002). The discrimination power can show the variables' power of influence in the class models. The four possible classification results are as follows: 1) a sample was assigned to the correct class (Right); 2) a sample was assigned to more than one class (More); 3) a sample cannot be assigned any class (Unknown); and 4) a sample was assigned to the wrong class (Wrong). A detailed description of SIMCA was reported by Wold (1976).

Table 1. Number of Samples in Calibration and Validation Sets by Different Eucalypt Knot Types

Knot types	Number of samples		
	Calibration set	Validation set	Total
Large knots	36	18	54
Small knots	40	20	60
Knot-free	40	20	60
All	116	58	174

RESULTS AND DISCUSSION

NIR Spectra Analysis

The mean spectra from original data and second-derivative spectra for all classes between 780 and 2500 nm are presented in Figs. 1 and 2. The raw spectra showed several differences in shape and absorption from each other, with the absorption strength of large and small knots obviously higher than that of normal wood. This may be due to the difference in the orientation of the microfibrils within fibers between knots and normal wood on the surface of veneers, as the microfibrils of knots' cells was substantially parallel to the NIR light incidence angle.

The NIR spectra also showed many absorption band peaks in the wavelength region of 1100 to 2500 nm, including prominent peaks around 1448, 1925, 2092, and 2267 nm. As reported in previous research (Alves *et al.* 2012), the absorbance at about 1448 nm is bound up with the first overtone of O-H stretching vibration from phenolic groups of lignin (Fackler and Schwanninger 2010).

The strong peak at approximately 1925 nm is primarily attributed to the O-H asymmetric stretching and O-H deformation from water (Workman and Weyer 2001; Siesler *et al.* 2002). The O-H and C-H deformation and O-H stretching vibration of cellulose and xylan are indicated by spectra changes at 2092 nm. Further, the overtone of O-H stretching and C-O stretching from lignin at 2267 nm also shows a change in absorption (Schwanninger *et al.* 2011).

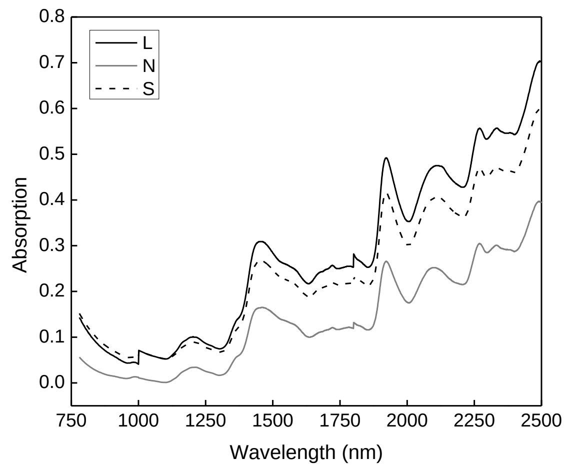

Fig. 1. The mean spectra from original data of large knots (L), small knots (S), and knot-free samples (N)

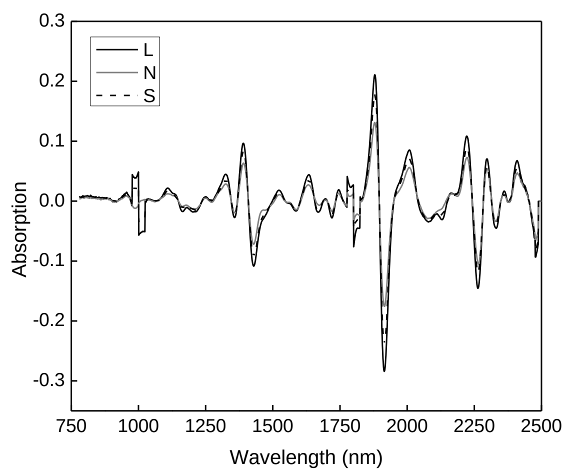

Fig. 2. The mean spectra from second-derivative spectra of large knots (L), small knots (S), and knot-free samples (N)

Detection of Knots of Veneer from Eucalypt

The NIR data regarding knots and normal wood in the calibration set were used to establish the PCA model of knot and knot-free wood, respectively. The accuracy of the SIMCA classification model was established through the validation set. Two different types of knots (large and small knots) were applied in the PCA knot model. Table 2 shows the SIMCA classification results for knot and knot-free eucalypt based on raw spectra at 5% significance level, indicating significant differences between different spectra acquired on the knot and knot-free area of the eucalypt.

Of the eucalypt knot samples, 84.2% were assigned to the correct class. The remaining knot types could not be assigned to any class, which may have resulted from some confusion among small knots, large knots, and normal wood. In the case of knot-free samples, classification accuracy was 60%. There were some samples (10%) that could not be assigned to any class. Thirty percent of eucalypt knot-free samples were assigned to more than one class, which may be explained by the fact that much information about normal wood existed in the spectra data of small knots on account of its size smaller than the NIR scanning area.

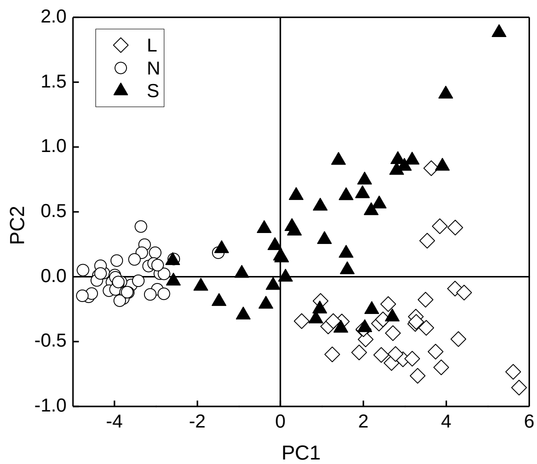

Fig. 3. The score plot of models, based on large knots (L), small knots (S), and knot-free (N) eucalypt samples

To further elucidate the classification results, spectra data from large knots, small knots, and knot-free samples were subjected to PCA analysis. The score plot is presented in Fig. 3. Principal components based on NIR spectra explained 99% of the variance of spectral data (PC1-98%, PC2-2%). From Fig. 3, only one cluster would be seen for all samples if there had been no differences in color. There was some overlap between small knots and both knot-free and large knot samples. Figure 4 shows the loadings of PC1 (98%), and the largest loadings on PC1 were from the wavelengths of 1448, 1926, and 2267 nm, which was coinciding with the above-mentioned absorption band peaks in the wavelength region of 1100 to 2500 nm.

Discrimination power spectra according to SIMCA classification analysis between large knots and normal wood, between large knots and small knots, and between small knots and normal wood are shown in Fig. 5.

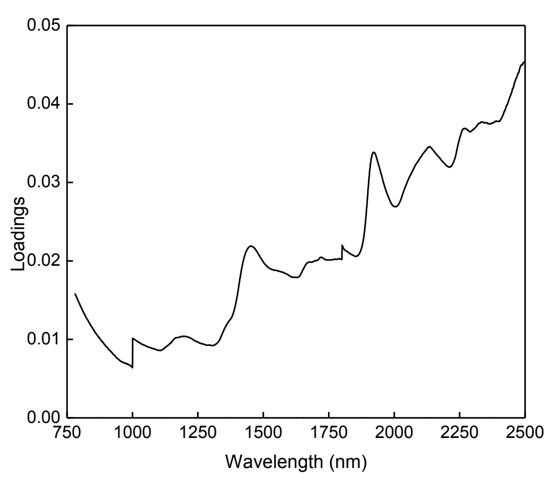

Fig. 4. Loadings for PC1 (98%)

As shown, most of the wavelength variables have discrimination power larger than 3 between large knots and normal wood, indicating that these spectra variables were the most important in the classification of large knots and normal wood. Discrimination power between small knots and large knots or normal wood were slightly less than 3, indicating the possibility that the spectra variables did not provide useful information in distinguishing between small knots and large knots or normal wood. These results provide some evidence for the confusion between small knots, large knots, and normal wood and the relatively poor classification results.

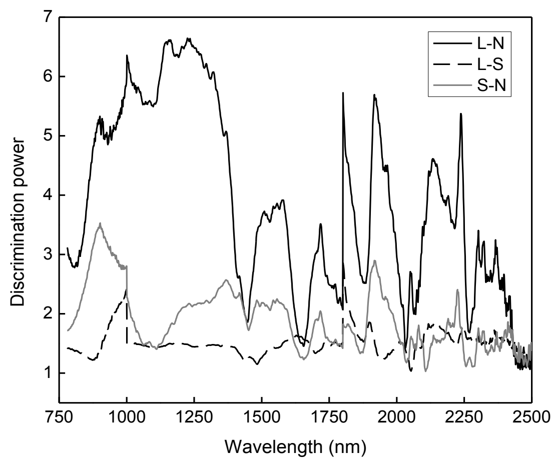

Fig. 5. Discrimination power spectra according to SIMCA classification analysis between large knots and normal wood (L-N), between large knots and small knots (L-S), and between small knots and normal wood (S-N)

Table 2. SIMCA Classification Result of Knots (Including Big and Small Knots) and Knot-Free Samples for Eucalypt at 5% Significance Level

Types	No. of PCs	Right	More	Unknown	Wrong
Knots (n = 38)	2	84.2% (32/38)	0% (0/38)	15.8% (6/38)	0% (0/38)
Knot-free (n = 20)	2	60% (12/20)	30% (6/20)	10% (2/20)	0% (0/20)

To further investigate the influence of small knots on the accuracy of the classification model, the data from large knots and normal wood were used in PCA analysis, with results provided in Table 3. The explained variance remained 99%. PC1 explained 91%, and PC2 explained 8%, of the knot spectra, and 96% (PC1) and 3% (PC2) of the knot-free spectra. As seen in Table 3, the classification accuracy of eucalypt knot samples decreased slightly, but no samples were assigned to more than one class, which is satisfactory. The classification accuracy of eucalypt knot-free samples improved from 60% to 90%. Apparently, the existence of small knots has an impact on whether knots are correctly distinguished from normal wood. The method of NIR spectra coupled with SIMCA may not be sensitive to the small knots because of the confusion between small knots and both large knots and normal wood.

Table 3. SIMCA Classification Result of Knots (Excluding Small Knots) and Knot-Free Samples for Eucalypt at 5% Significance Level

Types	No. of PCs	Right	More	Unknown	Wrong
Knots (exclude small knots) (n = 18)	2	77.8% (14/18)	0% (0/18)	22.2% (4/18)	0% (0/18)
Knot-free (n = 20)	2	90.0% (18/20)	0% (0/20)	10.0% (2/20)	0% (0/20)

Comparison Among Classification Results of Knot and Knot-Free Samples Based on Different Spectral Pretreatment Methods and Wavelength Ranges

Table 4 shows the SIMCA classification results for knot and knot-free samples in the validation set for the raw, first-derivative, second-derivative, and vector normalization spectra in the wavelength ranges of 780 to 2500 nm, 780 to 1100 nm, and 1100 to 2500 nm. The explained variance for each model exceeded 90%. The classification accuracy (*i.e.*, the rate of samples that were assigned to the correct class) of knot samples and normal wood reached 72.2 to 94.4% and 90 to 100%, respectively. No samples were assigned to more than one class or were wrongly assigned, although a few samples could not be assigned to any classes. This classification accuracy was much lower than the classification accuracy in our previous study on Masson pine (Yang *et al.* 2009), especially for the knot samples. This may be explained by the difference between the chemical composition of eucalypt and Masson pine knots, largely because of the latter's high resin content (Huang *et al*. 2011).

Table 4. Classification Results for Knot and Knot-Free Samples of Eucalypt

Pretreatment	Types	No. of PCs	Right (%)	More (%)	Unknown (%)	Wrong (%)
Raw spectra						
780–2500	L (n=18)	2	77.8	0	22.2	0
	N (n=20)	3	90.0	0	10.0	0
780–1100	L (n=18)	2	72.2	0	27.8	0
	N (n=20)	3	90.0	0	10.0	0
1100–2500	L (n=18)	2	83.3	0	16.7	0
	N (n=20)	2	100.0	0	0.0	0
First derivative						
780–2500	L (n=18)	5	88.9	0	11.1	0
	N (n=20)	9	95.0	0	5.0	0
780–1100	L (n=18)	3	72.2	0	27.8	0
	N (n=20)	3	90.0	0	10.0	0
1100–2500	L (n=18)	3	94.4	0	5.6	0
	N (n=20)	9	100.0	0	0	0
Second derivative						
780–2500	L (n=18)	4	94.4	0	5.56	0
	N (n=20)	7	100.0	0	0	0
780–1100	L (n=18)	4	83.3	0	16.7	0
	N (n=20)	2	95.0	0	5.0	0
1100–2500	L (n=18)	3	94.4	0	5.6	0
	N (n=20)	6	100.0	0	0	0
Vector normalization						
780–2500	L (n=18)	3	77.8	0	22.2	0
	N (n=20)	2	90.0	0	10.0	0
780–1100	L (n=18)	2	72.2	0	27.8	0
	N (n=20)	3	90.0	0	10.0	0
1100–2500	L (n=18)	6	77.8	0	22.2	0
	N (n=20)	2	90.0	0	10.0	0

Note: L stands for large knots and N stands for knot-free samples.

According to an analysis of the results of different pretreatment methods, it could be found that calibration models developed with the second-derivative-transformed NIR spectra exhibited the highest classification accuracy for individual classes, followed by models built with the first-derivative-transformed NIR spectra, models based on the raw spectra, and models based on vector-normalization-transformed NIR spectra. This may indicate that first-derivative or second-derivative transformation of spectral data could greatly improve the classification accuracy.

When comparing classification accuracy using different wavelength regions, it can be concluded that the accuracy of the whole NIR spectra region of 750 to 2500 nm and the restricted range of 1100 to 2500 nm were high. Given that the latter was even higher than the former, the restricted range of 1100 to 500 nm might provide the most useful information for the classification of knots samples and normal wood. Results based on the 780 to 1100 nm wavelength region were much less accurate, which might be explained by the characteristics of the near-infrared spectrum in Fig. 1, in which the spectrum between 780 and 1100 nm is relatively smooth and contains less vibration information regarding the chemical bonds of knots and normal wood, while the spectrum between 1100 and 2500 nm exhibits many absorption peaks resulting from C-H stretching and deformation, O-H stretching, and C-O stretching. Thus, NIR data on the wavelength region of 1100 to 2500 nm might be more useful than that from 780 to 2500 nm for classifying knots and normal wood on the surface of eucalypt veneers.

CONCLUSIONS

This study found that near infrared spectrometry (NIR) coupled with the soft independent modeling of class analogy (SIMCA) method could be used for the discrimination of knots on the surface of eucalypt veneers.

1. NIR spectroscopy in combination with SIMCA has enormous potential for detecting knots on the surface of eucalypt veneers, and models had higher classification accuracy with small knot (< 5 mm) data removed, probably because of property similarities and overlaps between small knots and both large knots and normal wood.
2. The method has a classification accuracy of 94.4% for knot samples of 10 to 15 mm in diameter and 100% accuracy for knot-free samples.
3. From the point of spectral pretreatment (including raw, first-derivative, second-derivative, and vector normalization spectra), models developed with second-derivative spectra resulted in the highest accuracy, followed by models developed with first-derivative spectra, models based on spectra transformed by vector normalization, and the model based on raw spectroscopy. In addition, the classification accuracy of models based on the wavelength region of 1100 to 2500 nm was higher than the whole region of 780 to 2500 nm as well as the wavelength range of 780 to 1100 nm.

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