A Preisach Based Model for the Characterisation of Magnetic Hysteresis

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Abstract

In this paper we present a model for hysteretic nonlinearities with non-local memories. This model can be used to describe hysteretic material behavior. Common applications are ferromagnetic or ferroelectric materials. Our model consists of an analytic function and a Preisach operator. Furthermore, we define a new Preisach weight function and introduce a method for the identification of the model parameters. Altogether, five parameters define the weight function and another two parameters are needed for the analytic function. With these seven parameters the model can be adapted very well to measured material curves. The model parameters are customized to a set of symmetric hysteresis curves of a soft magnetic material. After that, non-symmetric curves like the virgin curve are predicted very well by the model. It is especially useful, if forced magnetization, that appears beyond technical saturation, plays a role.

1. Introduction

For the simulation of sensors and actuators it is essential to have appropriate models for the involved materials. In a first step, linear approximations are often used. In a second step, nonlinear functions can describe the behavior more accurately. But when materials are involved, which incorporate memory effects, like ferromagnetic, magnetostrictive or piezoelectric materials, the need for models arises, which can reflect this memory. For the modeling of such materials, mathematical descriptions like the Preisach-Operator have been proposed [4, 3].
One of the practical problems that come up is to fit the weights of the Preisach Plane to a specific material. For piezoelectric materials an approach can be found in [2]. The authors of [1] have used Gaussian and Lorentzian functions to define a continous weight function for the Preisach Plane.

2. The Preisach Operator

In this paper, we deal with hysteresis nonlinearities including nonlocal memories. A precise definition of this special kind of hysteresis can be found in [3]: „The distinct feature of these nonlinearities is, that their future states depend on past histories of input variations. ... Indeed only some past input extrema leave their marks upon the future states.“
A mathematical operator which describes such behavior is the Preisach Operator. Here, we can give only a brief introduction to this operator, further information can be found in literature [3],[5]. The general formulation for the continuous Preisach hysteresis operator $\hat{\Gamma}$ is

$$f(t) = \hat{\Gamma} u(t) = \iint_{\alpha \geq \beta} \mu(\alpha, \beta) \hat{\gamma}_{\alpha\beta} u(t) \, d\alpha \, d\beta \ , \ (1)$$

where the time signals $u(t)$ and $f(t)$ denote the input and output. The weight function $\mu(\alpha, \beta)$ defines the shape of the hysteresis curve and will extensivly be discussed later. The operators $\hat{\gamma}_{\alpha\beta}$ can only have the discrete values 0 and 1. They resemble the “memory” of the hysteresis operator and are also often called “switching operators”. The integral is evaluated over the two dimensional, triangular-shaped Preisach Plane *S*.

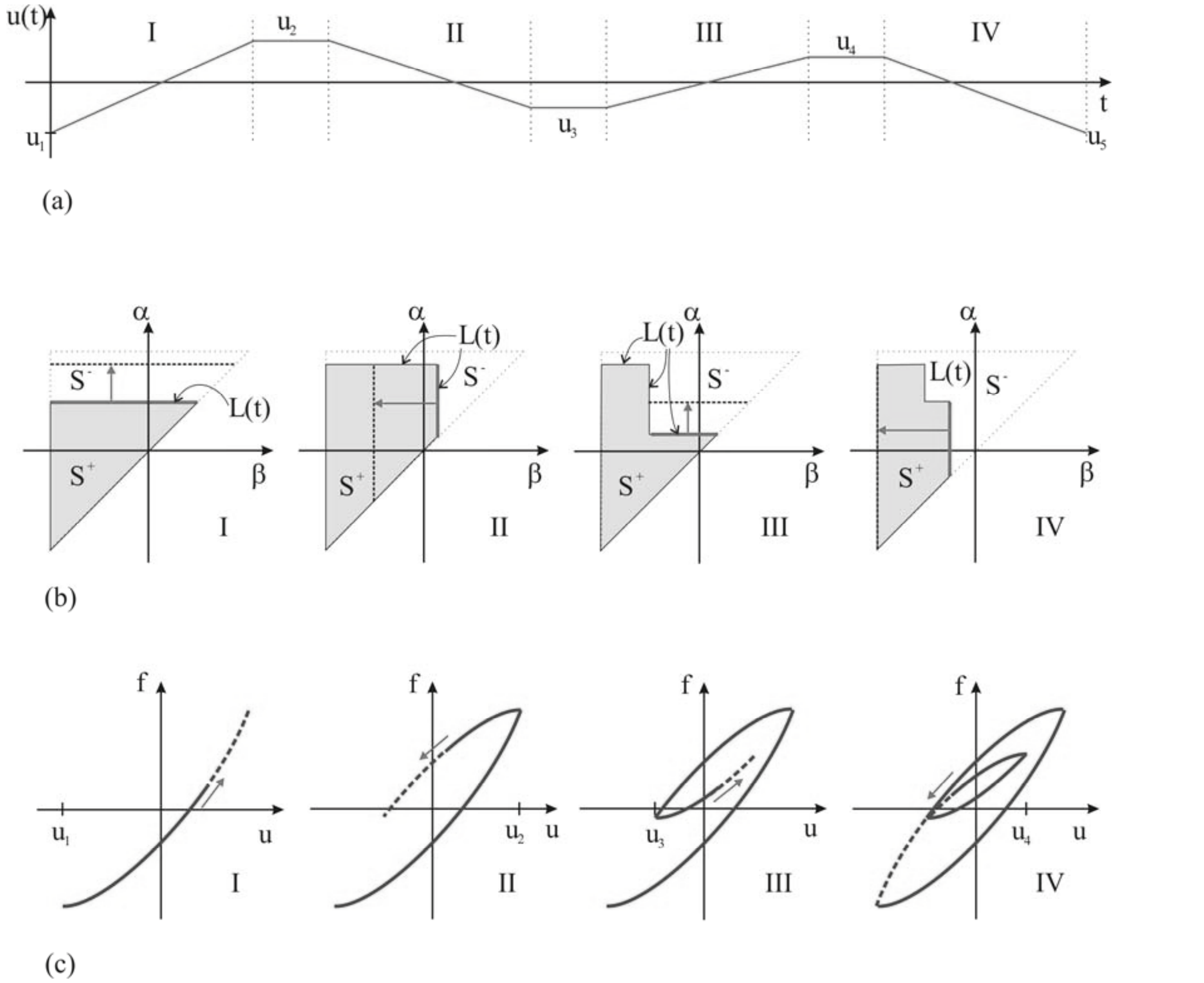

Fig. 1. Graphical representation of the Preisach operator. (a) Slope of an input example *u(t)*, (b) Preisach Plane with activated (S+) and not activated (S-) switching operators, (c) Resulting hysteresis curve [2].

In Fig. 1 it is demonstrated how the operators $\hat{\gamma}_{\alpha\beta}$ switch according to a specific input function *u(t)*. In the beginning all $\hat{\gamma}_{\alpha\beta}$ are reset to 0. For a rising slope of *u(t)*, the $\hat{\gamma}_{\alpha\beta}$ with the property $\alpha < u(t)$ are set to 1. For a falling slope of u(t), the $\hat{\gamma}_{\alpha\beta}$ with the property $\beta > u(t)$ are reset to 0. This devides the Preisach Plane S into one part with activated switching operators (S^+) and another part containing deactivated operators (S^-). The evaluation of the integral in Eq. 1 results in the hysteresis curve given in Fig. 1c.

The actual task discussed in this article is the definition of the weight function $\mu(\alpha,\beta)$. It has been mentioned, that this weight function defines the shape of the hysteresis curve and, therefore, has to be adapted to measured data.
In principle, there are two different methods. One possibility is to discretize the Preisach Plane, which results in a finite number of weights $\mu[\alpha,\beta]$ that have to be identified. The advantage of this approach is that there exist distinct mathematical regulations for the identification of the weights, as described in [3] and [6]. As a drawback it can be mentioned that for the identification process first-order reversal curves (FORC) are necessary. Another drawback is that a very irregular pattern of weights develops, that cannot be brought into context to the actual shape of the hysteresis curve in an intuitive way. As the number of independent parameters for a discretisation n is $(n^2)/2$, the question arrises, if the number of parameters for practical discretisations n>30 is not too high.
The approach which is discussed here suggests an analytical function with a small number of parameters to express the continuous weight function $\mu(\alpha,\beta)$. In the literature, a so called Gaussian weight function

$$\mu_G(\alpha,\beta) = A\exp\left(-\frac{1}{2}\left[\left(\frac{\beta-\alpha-2h}{2h}\sigma_1\right)^2 + \left(\frac{\beta+\alpha}{2h}\sigma_2\right)^2\right]\right)$$

with four parameters *A, h, σ1* and *σ2* can be found [1]. Also a Lorentzian function is mentioned

$$\mu_L(\alpha,\beta) = A\frac{1}{1+\left(\frac{\alpha+h}{h}\sigma_1\right)^2}\frac{1}{1+\left(\frac{\beta-h}{h}\sigma_2\right)^2}$$

with the same set of parameters [7].

The improvements we want to present here can be devided into three steps:

1. New weight function
The weight function we propose here contributes to the fact that the general shape of the outer hysteresis loop is often arc tangent-like. Therefore, the weight function should be similar to the derivative of the arc tangent-function. This leads to a new Derivative Arc Tangent function, the DAT weight function

$$\mu_{DAT}(\alpha,\beta) = \frac{A}{1+[(\alpha+\beta)\sigma_1]^2+[(\alpha-\beta-h)\sigma_2]^2}$$

With also four parameters *A, h,* $\sigma 1$ and $\sigma 2$.

2. Additional parameter
The DAT weight function can be further improved with help of an additional parameter η, which forms the corners of the hysteresis loop and makes the function suitable for a wide range of harder and softer magnetic materials. The weight function is then rewritten in its final form

$$\mu_{DAT}(\alpha,\beta) = \frac{A}{1+\{[(\alpha+\beta)\sigma_1]^2+[(\alpha-\beta-h)\sigma_2]^2\}^\eta}. \qquad (2)$$

3. Additional function for reversible (functional) part of material behaviour
One problem of the pure Preisach formulation of hysteresis as given in Eq. (1) arises from the fact, that the Preisach operator is defined for a closed intervall of input values *u(t).* Outside this intervall the result *f(t)* is constant. Refering to magnetic hysteresis, these constant values would be called the saturation magnetisation.

From a practical point of view this leads to two problems. First, if the model is to be used in numerical simulation, these constant parts of *f(t)* lead to numerical problems, because at these points the curve is not even locally reversible. Second, a correct value for the saturation is difficult to define. After technical saturation is reached and no more hysteresis can be observed, the magnetisation keeps increasing with the magnetic field due to an effected called “forced magnetisation”. It is more reasonable to model this effect with an analytical function than to include it into the Preisach operator. For this analytical function we choose again the arc tangent function as explained before.

This leads us to our final formulation for mapping the input *u(t)* to an output *v(t)*

$$v(t) = a \arctan bu(t) + \hat{\Gamma}u(t) \ .$$

As we use this formulation for magnetics, in the following our input *u(t)* is the magnetic field *H(t)* in A/m and our output *v(t)* is the Magnetisation *J(t)* in T.

3. Experimental Setup

For the identification of our model parameters to a specific material we use a **s**ymmetric set of **m**inor hysteresis **l**oops (SML). We measure these loops either with the Epstein apparatus as depicted in Fig. 2 or with a double-C-Yoke apparatus. Its principle is depicted in Fig. 3.
The Epstein apparatus works with the transformer principle. The primary current defines the H-field in the core. From the induced secondary voltage the magnetic flux B can be calculated by integration. The

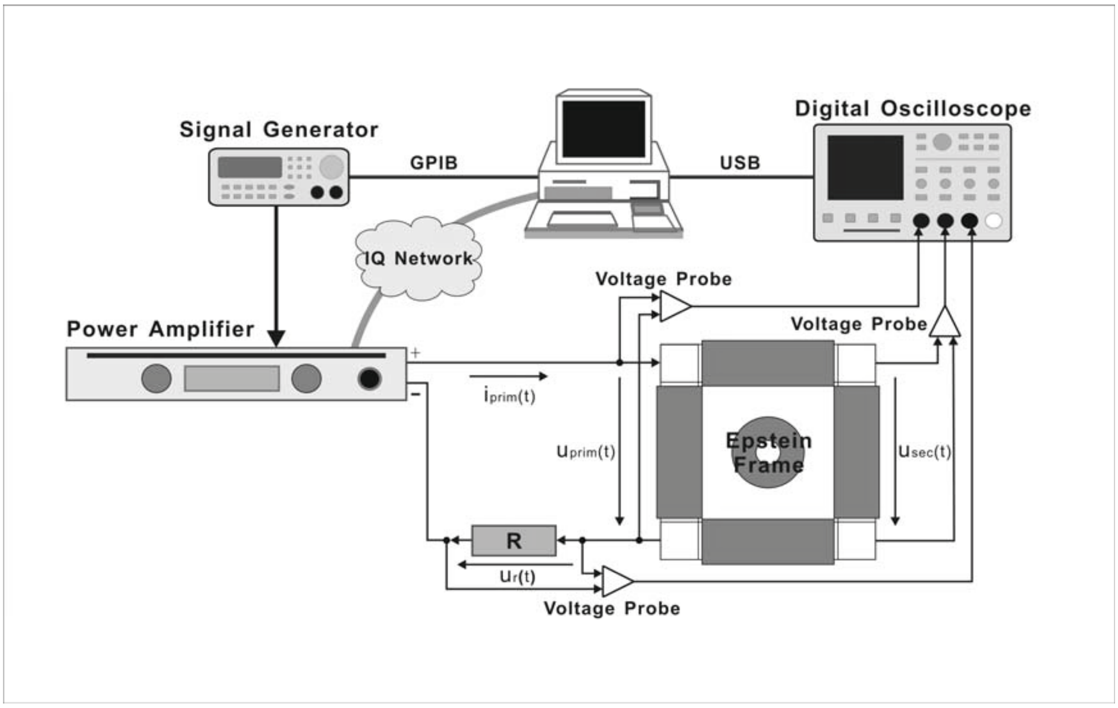

Fig. 2. Epstein setup for the precise measurement of outer and inner hysteresis loops of magnetic materials

advantage is that the H-field's variation in time can easily be defined. The drawback is that it is a global measurement and the complete core has to consist of the material under test.

In this sense, the Double C-Yoke is more flexible. Only the sheet depicted in Fig. 3 has to consist of the material under test. The flux Ψ is produced in the Yoke which is not shown here. Again, the B-field is calculated from a voltage induced in the "main flux coil". Additionally, the H-field has to be calculated from the voltage induced in the "leakage flux coil".

For further details about these measurement setups please refer to the literature [8].

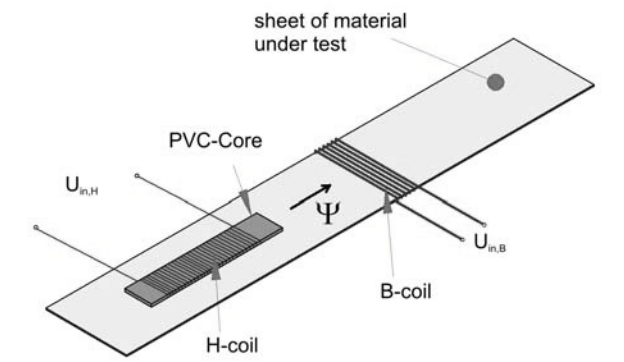

Fig. 2. Sheet of material in the Double C-Yoke

4. Results

In order to demonstrate our model we show some experimental validation of our simulated model prediction to measured data. Figure 4 shows a set of five measured symmetric hysteresis loops (solid lines) together with the model output (dashed lines). These loops have been used to adapt the model parameters with a nonlinear optimizer. The material under test is a soft magnetic steel.

It can clearly be seen that the material exhibits significant hysteresis only for H-fields in the range of $\pm$400A/m. Beyond this range there is still a significant gradient but no hysteresis. This is a typical material behavior where our model is useful: modeling the whole curve with the Preisach operator would be too costly. Dismissing the gradient for |H|>400A/m would cause large errors.

In this specific case the Preisach operator has been constrained to the closed, symmetric intervall [-400A/m,400A/m]. The Preisach operator has been normalized to these limits and the resulting weigth function as described by Eq. (2) is illustrated by the intensity plot in Fig. 5. Bright colour means high values, dark colour means low values. From the theory of Preisach as well as from the formulation of the weight function it is clear that all entries are of positive value.

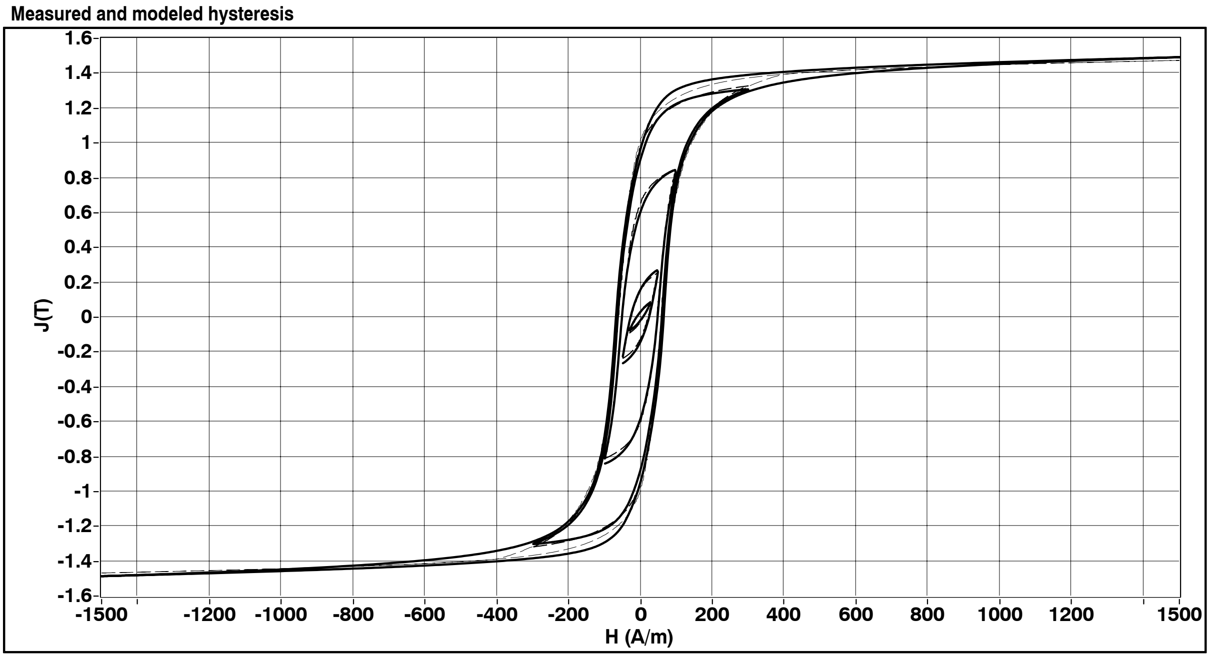

Fig. 4. Five symmetric hysteresis loops, measured (solid curves) and simulated (dashed curves)

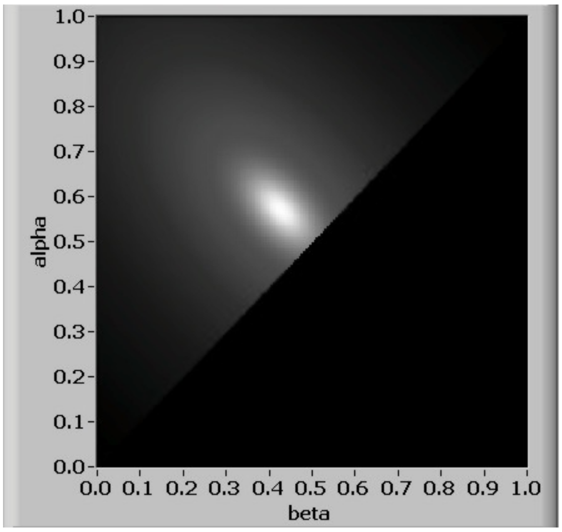

Fig. 5. Weights of the Preisach Plane. The coordinates have been normalized.

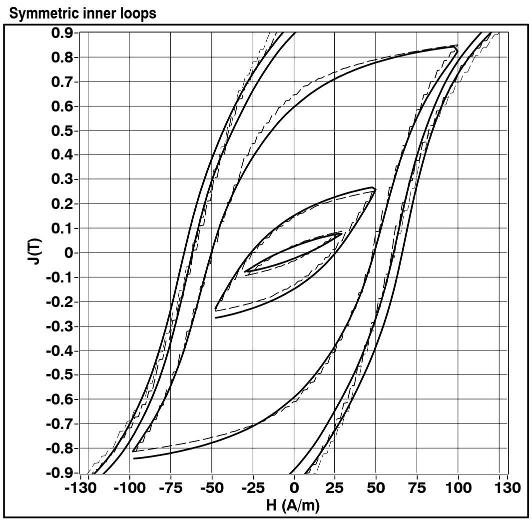

Fig. 6. Magnification of the inner loops

In Fig. 6 the inner loops in the range of +/-100A/m have been magnified. It can be noticed, how well the model matches the measured data. In Fig. 7, the area around H=400A/m has been magnified, where the intervall of the Preisach operator ends and passes into the analytical formulation. As the hysteresis in the measured data does not completely vanish for values above this limit, a significant gap between the model output and the measured data can be noticed. But it must be emphasized that this not a lack of the model, but just the decision of the user, who defines the intervall limits for the Preisach operator.

Figure 8 shows the measured loops in comparison to the predicted virgin curve as produced by the model output. It can be noticed that the virgin curve is running exactly through the tips of the measured minor loops.

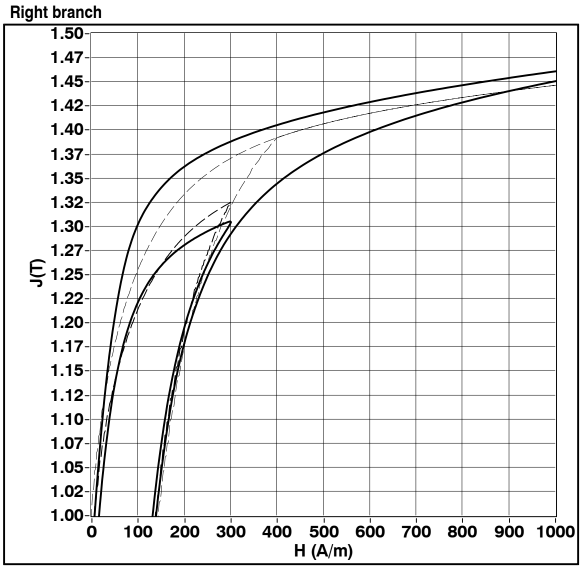

Fig. 7. Right branch of the hysteresis loops

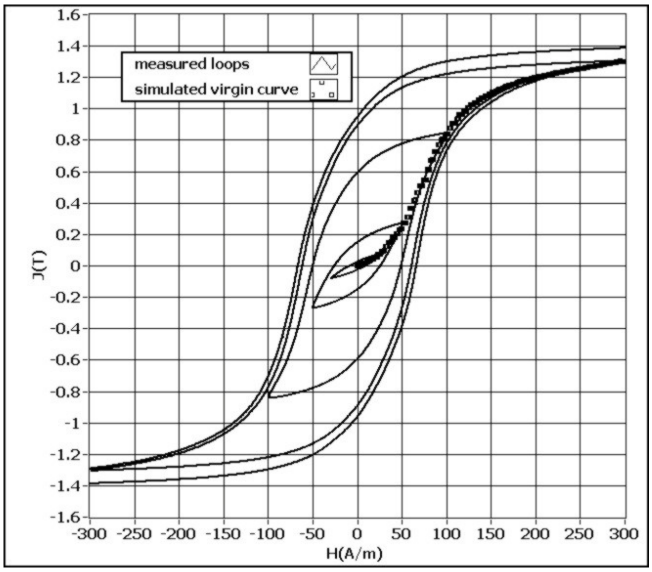

Fig. 8. Measured loops compared to the virgin curve

Conclusion

A new approach to hysteresis modeling with a Preisach operator has been presented. As important innovations it can be concluded:

1. The Derivative Arc Tangent weight function has been motivated, introduced and tested.
2. It has been expanded by an additional exponential parameter η. It could be shown that this additional parameter makes the weight function suitable for a wider range of hysteresis shapes.
3. A further development is the superposition of the Preisach operator with an analytical function. This is an important step to make the Preisach operator more useful for practical applications.

It could be shown that this model fits well to measured hysteresis loops of soft magnetic materials. It is now ready to be tested with further kinds of hysteresis aspects like magnetostrictive and piezoelectric ones.

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