THE NORMALIZED DIFFERENCE UNIT AS A METRIC FOR COMPARING IV CURVES

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ABSTRACT

A new quantitative measure of difference is proposed for comparing sets of transistor current-voltage (IV) curves. Conventional qualitative comparisons used, for example, to compare pulsed and static IV data are subjective. The proposed normalized difference unit (NDU) is a metric which can be used to state the difference between two sets of IV curves. It is shown in this paper that a plot of NDU versus pulse length can be used to isolate thermal and trapping time constants. In addition, the NDU can be used to numerically describe and compare the quality of model fits.

I. INTRODUCTION

For many years, sets of current-voltage (IV) curve data have been compared qualitatively. The degree to which the sets of IV curves are correlated is often determined by visual inspection in which it is decided that the curves either match well or deviate unacceptably. While quantitative comparisons have long been made between measured and modeled IV data for model-fitting purposes [1]-[3], the popularization of pulsed IV measurements [4]-[6] has intensified the need for a standardized general metric for IV comparisons. It is desired that such a metric be applicable to devices of all sizes and to IV comparisons of various types (pulsed versus static, measured versus modeled, pulsed versus pulsed with different quiescent bias points, etc.). In this paper, the formulation of such a unit is given, followed by examples of its use.

II. FORMULATION

A successful numerical solution to the problems caused by visual comparisons can be found in the proposed normalized difference unit (NDU), developed after analysis of other available metrics for varied uses [1]-[3]:

$$NDU = \frac{1}{N}\left(\frac{\sum_{i=1}^{N} \left| I_{DS1i} - I_{DS2i} \right|}{\left| I_{DSmean} \right|} \right), \qquad (1)$$

where I_{DS1i} and I_{DS2i} are the drain-source current values at the ith (V_{GS}, V_{DS}) points of measurement on the two current-voltage characteristics and I_{DSmean} is the average of the current values over all measured points from both characteristics:

$$I_{DSmean} = \frac{1}{2N}\sum_{i=1}^{N}(I_{DS1i} + I_{DS2i}). \qquad (2)$$

The NDU provides an equal weight for each data point, causing it to be an attractive metric for use in IV comparisons. The following examples reveal the results of studies performed at the University of South Florida which demonstrate the versatility of the NDU.

III. NUMERICAL DESCRIPTION OF THE DIFFERENCE BETWEEN PULSED AND STATIC IV RESULTS

The NDU can be used to give a representation of the size of overall differences between static and pulsed IV curves. In this example, the NDU comparing static and pulsed IV curves, measured by an Accent Optical Technologies Dynamic i(V) Analyzer (DiVA) model D210 [7], is given for two devices: a Tri-Quint CLY-5 GaAs MESFET and a Sirenza Microdevices SGA-9289 SiGe heterojunction bipolar transistor (HBT). The IV curves for these devices, respectively, are shown in Figures 1 and 2. To set a "noise floor" for the measurement, two IV data sets for "identical" measurement settings were compared to give the repeatability NDU for the instrument. The average NDU value for this comparison (for DiVA D210 pulsed IV measurements) was found to be 0.0038.

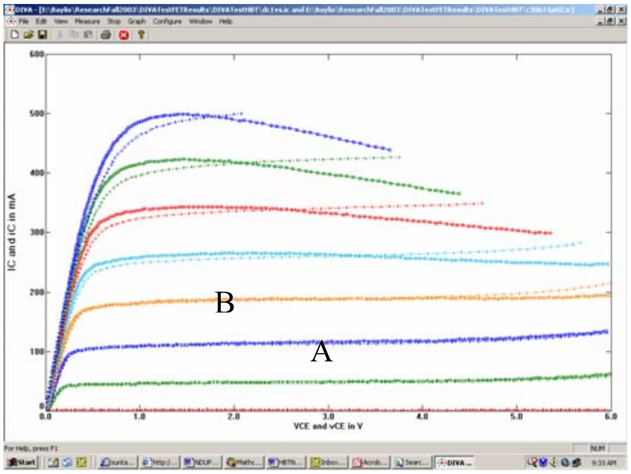


Figure 1. Static IV (Solid Lines) and Pulsed IV (Quiescent Bias Point: I_B = 1.5 mA, V_{CE} = 3.0 V, Pulse Length = 0.2 µs) (Dashed Lines) for the SGA-9289 HBT (NDU = 0.136)

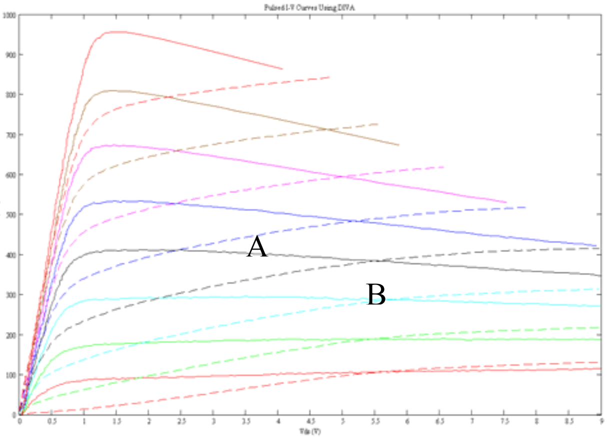


Figure 2. Static IV (Solid Lines) and Pulsed IV (Quiescent Bias Point: V_{GS} = -0.9 V, V_{DS} = 4.0 V, Pulse Length = 0.2 µs) (Dashed Lines) for the CLY-5 GaAs MESFET (NDU = 0.222)

An analysis of the HBT gives an NDU of 0.136 between static and pulsed IV results, while analysis of the MESFET gives a NDU of 0.222. Both results are well above the measurement repeatability "noise floor", so pulsed IV measurement results are significantly different from static IV results for each device. The NDU for the HBT is significantly lower than that of the MESFET, so it is concluded that there is less difference between the pulsed and static IV results for the HBT than for the MESFET, leading to the prediction that the use of static IV data for model extraction would result in a larger error in the FET modeled results than for the HBT.

IV. DETERMINATION OF THE TYPES OF EFFECTS PRESENT IN A DEVICE AND THEIR TIME CONSTANTS

According to the literature, the inaccuracy of static DC IV measurements can be attributed to trapping and thermal effects that occur at low frequencies [4]. Scott has proposed a transient analysis method for time-constant extraction and effect isolation [8]. A similar analysis can be performed using the NDU. The NDU can be measured between pulsed IV results from some quiescent bias point at different pulse lengths and static IV results. Theoretically, the longest pulse lengths that can be used to avoid contamination by thermal and trapping effects (labeled the "minimum time constants") can be observed from this plot of NDU versus pulse length. In a second plot, an NDU-versus-pulse length characteristic can be generated to compare two sets of pulsed IV curves taken from quiescent bias points of equal power dissipation. Taking the difference between pulsed IV data taken from quiescent bias points of identical power dissipation eliminates thermal effects as the cause of differences between the results [8], allowing the conclusion that minimum time constants isolated from this plot correspond to trapping effects and the remaining effects from the first plot are thermal.

This analysis was performed for the CLY-5 GaAs MESFET. In the first NDU comparison, pulsed IV data taken with all pulse lengths available on the instrument from a Class A quiescent bias point of V_{GS} = -0.9 V, V_{DS} = 4.0 V (point "A" in Fig. 2) was compared to static IV data. Second, pulsed IV measurements were performed for a quiescent bias point of V_{GS} = -1.2 V, V_{DS} = 5.5 V (point "B" in Fig. 2), a bias point with a power dissipation equal to that of the first quiescent point. A plot of NDU versus pulse length for this device is shown in Fig. 3. Three distinct minimum time constants are observed in the static-to-pulsed comparison (solid line): 0.5 μs, 50 μs, and 500 μs. Each of these appears as the pulse length immediately before a significant reduction in the slope of the NDU curve. The pulsed-to-pulsed IV comparison (dashed line) for equipower quiescent bias points shows that the 0.5 μs and 500 μs minimum time constants relate to trapping effects. Thus it is concluded that the 50 μs effect is thermal. These results are summarized in Table I. The result of two trapping effects with vastly differing minimum time constants is consistent with results presented in the literature [6],[9],[10].

A similar analysis was performed for the SiGe HBT and resulted in isolation of a single thermal effect, consistent with results presented in the literature [11]. For a device with no trapping effects, the NDU comparing pulsed IV results taken from quiescent points of equal power dissipation (points "A" and "B" in Fig.1; point "A" is I_B = 1.5 mA, V_{CE} = 3.0 V, while point "B" is I_B = 2.1 mA, V_{CE} = 2.0 V), is flat, as shown by the plots of Fig. 4. The HBT results are also summarized in Table I.

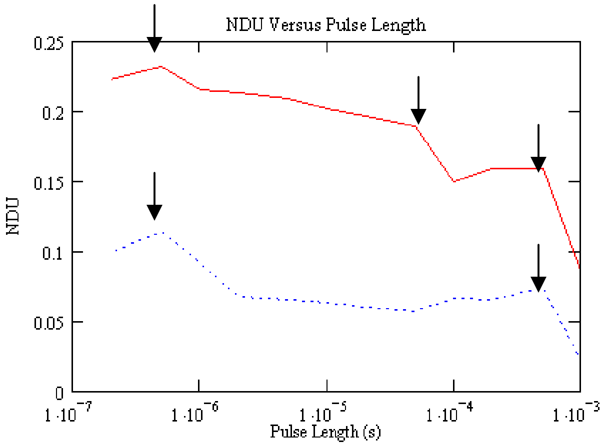


Figure 3. Plots of Normalized Difference Unit (NDU) for a GaAs FET. The solid line shows the NDU comparing static and pulsed (Quiescent Bias Point: Vgs = -0.9 V, Vds = 4.0 V) IV measurements versus pulse length. The dashed line gives the NDU comparing pulsed measurements from quiescent bias points of equal power dissipation. Arrows are used to denote the estimated effect minimum time constants.

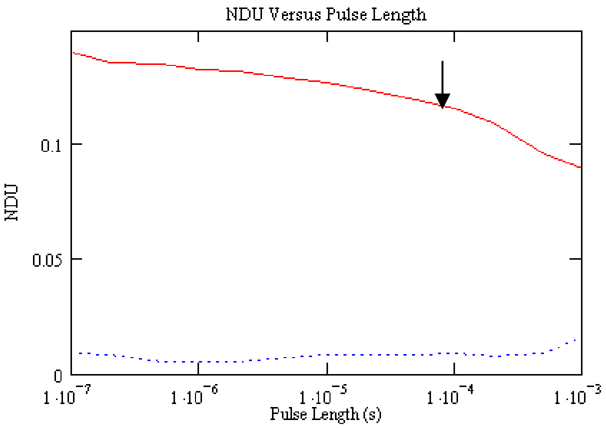


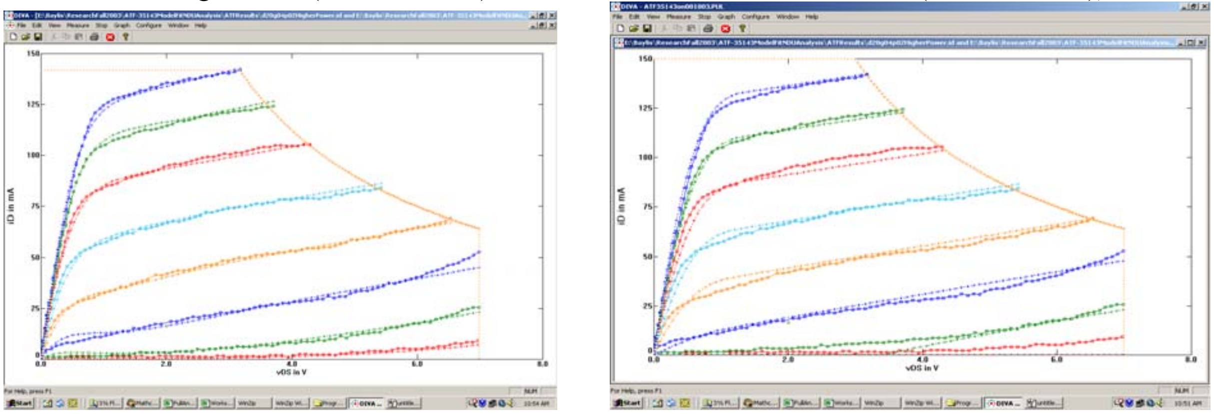
Figure 4. Plots of Normalized Difference Unit (NDU) for a SiGe HBT. The solid line shows NDU Comparing Static and Pulsed (Quiescent Bias Point: I_B = 1.5 mA, V_{CE} = 3.0 V) IV measurements versus pulse length. The dashed line gives the NDU comparing pulsed measurements from quiescent bias points of equal power dissipation. Arrows are used to denote the estimated effect minimum time constants.

TABLE I: MEASURED FET AND BJT EFFECTS, CUTOFF FREQUENCIES, AND MINIMUM TIME CONSTANTS

Effect	SiGe HBT Minimum Time Constant	GaAs MESFET Minimum Time Constant
Fast Trapping	-	0.5 µs
Thermal	100 µs	50 µs
Slow Trapping	-	500 µs

V. DETERMINATION OF A BEST-FIT MODEL TO DATA

Another useful way in which the NDU can be used is to numerically determine the best-fit model of several candidate models to a set of IV data. The NDU is used to compare the measured and modeled IV data for each model, and the model corresponding to the lowest value of NDU may be said to provide the best overall fit in the (V_{GS}, V_{DS}) region of evaluation. In this experiment, the model fitting capabilities of the DiVA software were used to perform a TOM1 fit [12], an Angelov fit [13], and a Statz fit [14]. The model fitting was performed for pulsed IV data measured on a DiVA 225 for a ATF-35143 400 µm pseudomorphic high electron mobility transistor (PHEMT), manufactured by Agilent Technologies. Figure 7 displays the measured and modeled data for the three fits used in the experiment and the NDU values obtained for the fits. A qualitative examination of the plots seems to show that, for the chosen device, the Statz model does a very poor job of modeling the curves in the breakdown region and also provides some discrepancies in the knee region. The TOM1 model results seem to match the measured data better at breakdown and in the knee region better than the Statz model, but not nearly as well as the Angelov model, which does an excellent job of modeling in the knee region and provides significantly better results in the breakdown region. Indeed, the NDU analysis confirms this qualitative examination, as the NDU value for the Angelov fit (0.018) is significantly lower than that of the TOM1 (0.032) and Statz (0.062) model fits.


Full Angelov Fit (NDU = 0.018)

TOM1 Fit (NDU = 0.032))

Statz Fit (NDU = 0.062)

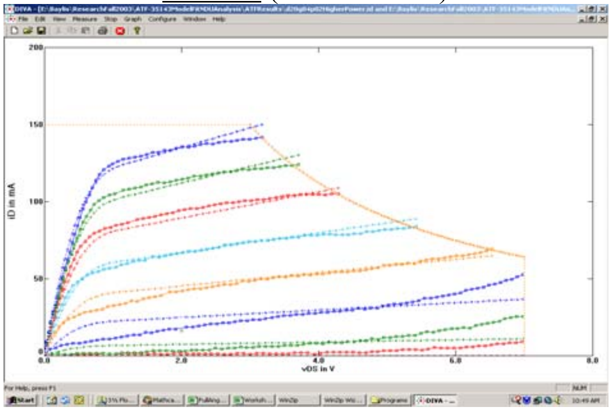


Figure 7. Angelov, TOM1, and Statz Fits to Pulsed IV Data for the Agilent ATF-35143 PHEMT (Measured IV Curves = Solid Lines, Measured IV Curves = Dashed Lines). The associated NDU values for each of the fits is also shown.

To give information about the regions of fit of the different models, a set of normalized difference functions can be constructed. These functions give the normalized difference as a function of one or both of the variables V_{GS}, V_{DS}. The normalized difference function $D(V_{GS}, V_{DS})$ is defined as follows:

$$D(V_{GS}, V_{DS}) = \left(\left| \frac{I_{DS1}(V_{GS}, V_{DS}) - I_{DS2}(V_{GS}, V_{DS})}{I_{DSmean}} \right| \right) \qquad (7)$$

This function produces a three-dimensional surface plot of the normalized difference as a function of the value in the (V_{GS}, V_{DS}) plane. Two-dimensional plots often provide a less complicated graphical analysis, and the functions $D(V_{GS})$ and $D(V_{DS})$ are often sufficient to show regional trends in the curve differences. In this manner, the normalized difference is given as a function of one of the variables while averaged over all values of the other variable. That is, $D(V_{GS})$ is the normalized difference averaged over all values of V_{DS} and given as a function of V_{GS}, while $D(V_{DS})$ is the normalized difference averaged over all values of V_{GS} and given as a function of V_{DS}. These functions are formally defined as follows:

$$D(V_{GS}) = \frac{1}{L} \sum_{i=1}^{L} \left(\left| \frac{I_{DS1}(V_{GS}, V_{DSi}) - I_{DS2}(V_{GS}, V_{DSi})}{I_{DSmean}} \right| \right) \qquad (8)$$

$$D(V_{DS}) = \frac{1}{M} \sum_{i=1}^{M} \left(\left| \frac{I_{DS1}(V_{GSi}, V_{DS}) - I_{DS2}(V_{GSi}, V_{DS})}{I_{DSmean}} \right| \right) \qquad (9)$$

Figure 8 gives plots of $D(V_{GS})$ and $D(V_{DS})$ for the Angelov, TOM1, and Statz fits.

In the Figure 8 plots, it can be observed that the normalized difference is greatest, in general, for the Statz fit (as given by the NDU values). The plots of $D(V_{DS})$ all reach their maximum values for high values of V_{DS}, indicating that the poorest region of fit for all three models is the breakdown region. The $D(V_{GS})$ function for the Statz model shows that the Statz model fit is relatively poor for a gate voltage of -0.4 V. An observation of the IV curves in Figure 6 verifies this (the -0.4 V curve is the third from the bottom), as the measured and modeled curves are greatly different in both the knee region and the breakdown region. The poor Statz fit in the breakdown region causes the $D(V_{DS})$ plot to exceed 0.1 for $V_{DS} > 5.5$ V.

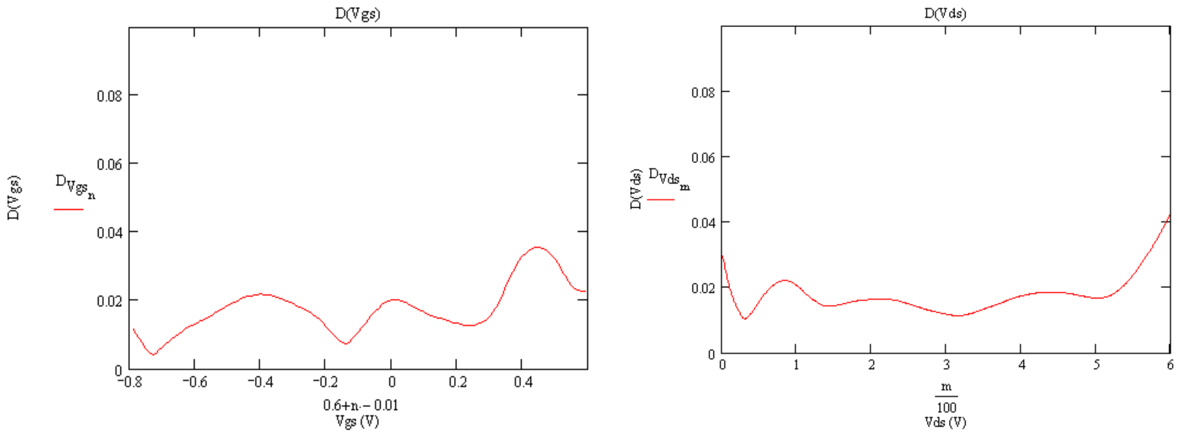
It is proposed that the NDU is an excellent decision-making metric for model-fitting applications. Provided the range of desired fit has been properly measured, the fits of the models can be evaluated quantitatively instead of qualitatively. This example also shows how a graphical analysis with the normalized difference functions $D(V_{GS})$ and $D(V_{DS})$ can be used to enhance the NDU analysis of IV curve differences with the NDU by giving a numerical measure of the IV curve correspondences in different regions.

VI. CONCLUSIONS

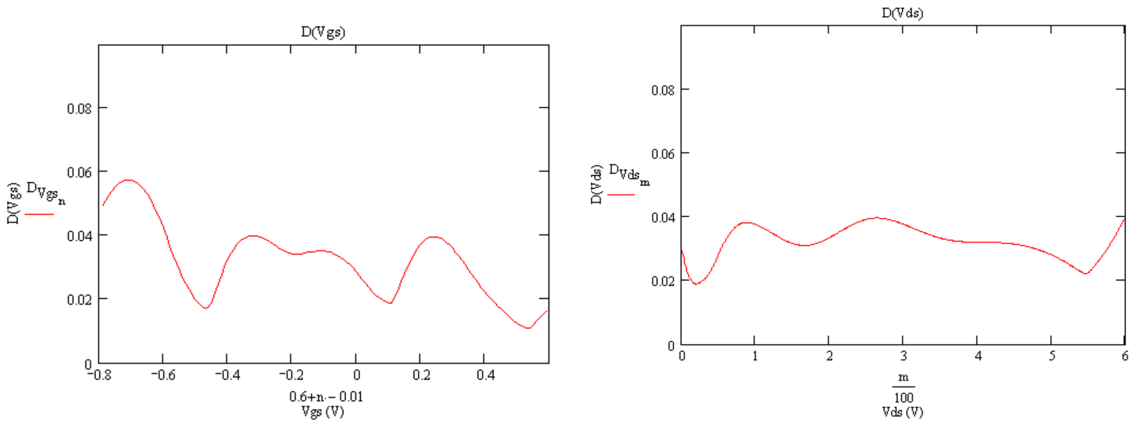
The normalized difference unit is proposed as a metric for IV curve comparison. The quantification of IV curve comparisons opens the door to numerous opportunities for analysis. Comparison of pulsed and static IV curve differences, isolation of thermal and trapping effects and their minimum time constants, and the numerical description of model fits are examples of the use of this metric to provide information that is useful in obtaining accurate RF and microwave device characterization. In addition to the examples shown in this paper, the NDU has shown to be helpful in finding the thermal capacitance [15] and examining the effects of pulse separation on pulsed IV results [16], as well as comparing the correspondence of thermally corrected IV curves to measured pulsed IV results [17].

Angelov:

$D(V_{GS})$ $D(V_{DS})$



TOM1:



Statz:

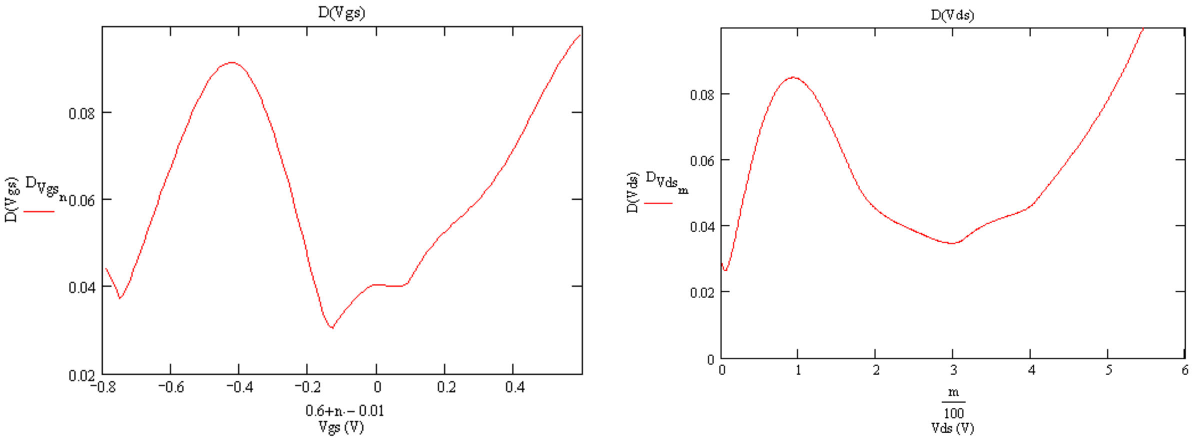


Figure 8. Plots of $D(V_{GS})$ (left) and $D(V_{DS})$ (right) for Three Model Fits to the ATF-35143 PHEMT.

ACKNOWLEDGMENTS

The authors wish to thank Mr. William Clausen from Modelithics, Inc. of Tampa, Florida, for providing valuable expertise and assisting with the setup for many of these measurements. In addition, gratitude is expressed to Dr. Peter Ladbrooke and Dr. James Bridge of Accent Optical Technologies and Dr. Walter Curtice of W.R. Curtice Consulting for their insightful comments and suggestions. Finally, it is gratefully acknowledged that this work has been partially funded by a fellowship grant from the Automatic RF Techniques Group (ARFTG).

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