

MATRIX DIFFERENTIAL CALCULUS WITH APPLICATIONS IN STATISTICS AND ECONOMETRICS

MATRIX DIFFERENTIAL CALCULUS WITH APPLICATIONS IN STATISTICS AND ECONOMETRICS IS A FUNDAMENTAL MATHEMATICAL TOOL THAT EXTENDS CLASSICAL CALCULUS TO FUNCTIONS INVOLVING MATRICES. THIS SPECIALIZED BRANCH OF CALCULUS PLAYS A CRITICAL ROLE IN THE DEVELOPMENT AND ANALYSIS OF STATISTICAL MODELS AND ECONOMETRIC TECHNIQUES, WHERE MATRIX EXPRESSIONS FREQUENTLY ARISE. UNDERSTANDING MATRIX DIFFERENTIAL CALCULUS ENABLES RESEARCHERS AND PRACTITIONERS TO EFFICIENTLY COMPUTE GRADIENTS, HESSIANS, AND OTHER DERIVATIVES ESSENTIAL FOR OPTIMIZATION, ESTIMATION, AND INFERENCE IN MULTIVARIATE SETTINGS. THIS ARTICLE EXPLORES THE CORE CONCEPTS OF MATRIX DIFFERENTIAL CALCULUS, ITS NOTATION, AND PROPERTIES, FOLLOWED BY DETAILED APPLICATIONS IN STATISTICS AND ECONOMETRICS. KEY TOPICS INCLUDE THE DIFFERENTIATION OF MATRIX FUNCTIONS, VECTORIZATION TECHNIQUES, AND THE USE OF MATRIX CALCULUS IN MAXIMUM LIKELIHOOD ESTIMATION, GENERALIZED METHOD OF MOMENTS, AND MULTIVARIATE REGRESSION ANALYSIS. READERS WILL GAIN A COMPREHENSIVE UNDERSTANDING OF HOW MATRIX DIFFERENTIAL CALCULUS FACILITATES ADVANCED STATISTICAL MODELING AND ECONOMETRIC ANALYSIS.

- FUNDAMENTALS OF MATRIX DIFFERENTIAL CALCULUS
- MATRIX CALCULUS NOTATION AND RULES
- APPLICATIONS IN STATISTICS
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- ADVANCED TOPICS AND COMPUTATIONAL TECHNIQUES

FUNDAMENTALS OF MATRIX DIFFERENTIAL CALCULUS

MATRIX DIFFERENTIAL CALCULUS IS A BRANCH OF MATHEMATICS THAT DEALS WITH THE DIFFERENTIATION OF FUNCTIONS WHOSE INPUTS AND OUTPUTS ARE MATRICES. UNLIKE SCALAR CALCULUS, MATRIX CALCULUS REQUIRES CAREFUL HANDLING OF DIMENSIONS, ORDERING, AND THE PROPERTIES OF MATRIX OPERATIONS SUCH AS TRANSPOSITION AND MULTIPLICATION. THIS FIELD PROVIDES THE MATHEMATICAL FOUNDATION FOR ANALYZING MULTIVARIATE FUNCTIONS, WHICH ARE UBIQUITOUS IN STATISTICS AND ECONOMETRICS. AT ITS CORE, MATRIX DIFFERENTIAL CALCULUS ENABLES THE COMPUTATION OF DERIVATIVES IN FORMS SUITABLE FOR OPTIMIZATION AND THEORETICAL DERIVATIONS IN HIGH-DIMENSIONAL DATA CONTEXTS.

DEFINITION AND BASIC CONCEPTS

MATRIX DIFFERENTIAL CALCULUS INVOLVES THE STUDY OF DIFFERENTIALS AND DERIVATIVES OF MATRIX-VALUED FUNCTIONS. GIVEN A FUNCTION $F: \mathbb{R}^{m \times n} \rightarrow \mathbb{R}^p$, THE GOAL IS TO FIND THE DERIVATIVE OR DIFFERENTIAL OF F WITH RESPECT TO THE MATRIX ARGUMENT. THIS REQUIRES EXTENDING NOTIONS SUCH AS THE GRADIENT AND JACOBIAN FROM VECTORS TO MATRICES. THE DIFFERENTIAL OF A MATRIX FUNCTION IS OFTEN EXPRESSED USING THE CONCEPT OF THE FRÉCHET DERIVATIVE, WHICH GENERALIZES THE DERIVATIVE TO VECTOR SPACES EQUIPPED WITH A NORM.

IMPORTANCE IN MULTIVARIATE ANALYSIS

MULTIVARIATE ANALYSIS OFTEN INVOLVES FUNCTIONS MAPPING VECTORS OR MATRICES TO SCALARS OR OTHER MATRICES. FOR EXAMPLE, VARIANCE-COVARIANCE MATRICES, REGRESSION COEFFICIENT MATRICES, AND LIKELIHOOD FUNCTIONS ARE ALL EXPRESSED IN MATRIX FORM. MATRIX DIFFERENTIAL CALCULUS FACILITATES THE DERIVATION OF GRADIENTS AND HESSIANS CRITICAL FOR ESTIMATION AND HYPOTHESIS TESTING. ITS IMPORTANCE IS AMPLIFIED IN HIGH-DIMENSIONAL SETTINGS, WHERE VECTOR AND MATRIX REPRESENTATIONS IMPROVE COMPUTATIONAL EFFICIENCY AND CLARITY OF ANALYTICAL RESULTS.

MATRIX CALCULUS NOTATION AND RULES

PROPER NOTATION AND UNDERSTANDING OF MATRIX CALCULUS RULES ARE ESSENTIAL TO CORRECTLY APPLY MATRIX DIFFERENTIAL CALCULUS. THIS SECTION OUTLINES THE STANDARD CONVENTIONS AND FUNDAMENTAL RULES USED IN THE DIFFERENTIATION OF MATRIX FUNCTIONS, ENSURING PRECISION AND AVOIDING COMMON PITFALLS IN CALCULATIONS.

COMMON NOTATIONS

MATRIX CALCULUS USES VARIOUS NOTATIONS TO EXPRESS DERIVATIVES SUCCINCTLY:

- $\frac{\partial}{\partial X}$: PARTIAL DERIVATIVE WITH RESPECT TO MATRIX X .
- dX : DIFFERENTIAL OF THE MATRIX X .
- $\text{vec}(X)$: VECTORIZATION OPERATOR THAT STACKS THE COLUMNS OF X INTO A SINGLE VECTOR.
- $\text{tr}(\cdot)$: TRACE OPERATOR, SUMMING THE DIAGONAL ELEMENTS OF A MATRIX.
- $\otimes$: KRONECKER PRODUCT, USED TO EXPRESS DERIVATIVES IN VECTORIZED FORM.

KEY DIFFERENTIATION RULES

THE FOLLOWING ARE FUNDAMENTAL RULES IN MATRIX DIFFERENTIAL CALCULUS:

1. **LINEARITY:** THE DIFFERENTIAL OF A SUM IS THE SUM OF DIFFERENTIALS, I.E., $d(A + B) = dA + dB$.
2. **PRODUCT RULE:** FOR MATRIX PRODUCTS, $d(AB) = dA \cdot B + A \cdot dB$.
3. **TRACE RULE:** THE DIFFERENTIAL OF THE TRACE SATISFIES $d \text{tr}(AB) = \text{tr}(dA \cdot B) + \text{tr}(A \cdot dB)$.
4. **CHAIN RULE:** FOR COMPOSITE FUNCTIONS, THE DERIVATIVE FOLLOWS THE CHAIN RULE ADAPTED FOR MATRIX ARGUMENTS.

MASTERING THESE RULES ALLOWS FOR THE SYSTEMATIC DERIVATION OF GRADIENTS AND HESSIANS FOR COMPLEX MATRIX FUNCTIONS ENCOUNTERED IN STATISTICAL AND ECONOMETRIC MODELS.

APPLICATIONS IN STATISTICS

MATRIX DIFFERENTIAL CALCULUS FINDS EXTENSIVE USE IN STATISTICAL THEORY AND METHODOLOGY, PARTICULARLY IN MULTIVARIATE STATISTICS WHERE MATRIX EXPRESSIONS ARE STANDARD. THIS SECTION DESCRIBES SEVERAL KEY APPLICATIONS AND ILLUSTRATES HOW MATRIX CALCULUS SIMPLIFIES DERIVATIONS AND COMPUTATIONS.

MAXIMUM LIKELIHOOD ESTIMATION (MLE)

MAXIMUM LIKELIHOOD ESTIMATION OFTEN INVOLVES OPTIMIZING A LOG-LIKELIHOOD FUNCTION THAT DEPENDS ON MATRIX PARAMETERS SUCH AS COVARIANCE MATRICES AND REGRESSION COEFFICIENT MATRICES. MATRIX DIFFERENTIAL CALCULUS PROVIDES A STREAMLINED APPROACH TO COMPUTING THE GRADIENT AND HESSIAN MATRICES NEEDED FOR ITERATIVE OPTIMIZATION ALGORITHMS LIKE NEWTON-RAPHSON AND FISHER SCORING.

MULTIVARIATE REGRESSION ANALYSIS

IN MULTIVARIATE REGRESSION, THE RESPONSE AND PREDICTOR VARIABLES ARE OFTEN ORGANIZED INTO MATRICES. THE ORDINARY LEAST SQUARES ESTIMATOR AND ITS PROPERTIES ARE DERIVED USING MATRIX CALCULUS, ENABLING CONCISE EXPRESSIONS FOR ESTIMATORS AND THEIR VARIANCES. DIFFERENTIATION OF MATRIX FUNCTIONS IS CRUCIAL IN DERIVING THE NORMAL EQUATIONS AND ASSESSING ESTIMATOR BEHAVIOR.

COVARIANCE MATRIX ESTIMATION

ESTIMATING COVARIANCE MATRICES AND THEIR FUNCTIONS REQUIRES DIFFERENTIATION WITH RESPECT TO MATRIX ARGUMENTS. MATRIX DIFFERENTIAL CALCULUS AIDS IN DERIVING ESTIMATORS' PROPERTIES, SUCH AS THE FISHER INFORMATION MATRIX FOR COVARIANCE PARAMETERS, AND FACILITATES HYPOTHESIS TESTING INVOLVING COVARIANCE STRUCTURES.

APPLICATIONS IN ECONOMETRICS

ECONOMETRIC MODELS FREQUENTLY INCORPORATE MATRIX FORMULATIONS TO ANALYZE ECONOMIC DATA INVOLVING MULTIPLE VARIABLES AND TIME PERIODS. MATRIX DIFFERENTIAL CALCULUS IS INTEGRAL TO DERIVING ESTIMATORS, PERFORMING INFERENCE, AND DEVELOPING ADVANCED ECONOMETRIC TECHNIQUES.

GENERALIZED METHOD OF MOMENTS (GMM)

THE GMM FRAMEWORK RELIES ON MOMENT CONDITIONS EXPRESSED AS FUNCTIONS OF PARAMETER MATRICES AND DATA MATRICES. DERIVATIVES OF THESE MOMENT FUNCTIONS WITH RESPECT TO PARAMETERS ARE ESSENTIAL FOR CONSTRUCTING EFFICIENT ESTIMATORS AND CALCULATING ASYMPTOTIC VARIANCES. MATRIX CALCULUS SIMPLIFIES THESE DERIVATIVE CALCULATIONS, MAKING GMM A PRACTICAL ESTIMATION METHOD IN COMPLEX MODELS.

VECTOR AUTOREGRESSIONS (VAR)

VAR MODELS ANALYZE THE DYNAMIC RELATIONSHIPS AMONG MULTIPLE TIME SERIES VARIABLES. PARAMETER ESTIMATION AND INFERENCE INVOLVE MATRIX FUNCTIONS OF LAG COEFFICIENTS AND COVARIANCE MATRICES. MATRIX DIFFERENTIAL CALCULUS ENABLES THE DERIVATION OF LIKELIHOOD FUNCTIONS AND THEIR DERIVATIVES, ENHANCING THE EFFICIENCY OF ESTIMATION AND FORECASTING.

PANEL DATA MODELS

PANEL DATA ECONOMETRICS DEALS WITH DATA SETS CONTAINING OBSERVATIONS OVER TIME FOR MULTIPLE ENTITIES. ESTIMATING FIXED EFFECTS, RANDOM EFFECTS, AND DYNAMIC PANEL DATA MODELS OFTEN INVOLVES DIFFERENTIATING MATRIX-VALUED FUNCTIONS. MATRIX DIFFERENTIAL CALCULUS FACILITATES THE DERIVATION OF SCORE FUNCTIONS AND INFORMATION MATRICES CRUCIAL FOR MAXIMUM LIKELIHOOD AND QUASI-MAXIMUM LIKELIHOOD ESTIMATION.

ADVANCED TOPICS AND COMPUTATIONAL TECHNIQUES

BEYOND FUNDAMENTAL APPLICATIONS, MATRIX DIFFERENTIAL CALCULUS ENCOMPASSES ADVANCED TOPICS AND COMPUTATIONAL METHODS THAT ENHANCE ITS UTILITY IN STATISTICS AND ECONOMETRICS.

VECTORIZATION AND THE KRONECKER PRODUCT

VECTORIZATION TRANSFORMS MATRICES INTO VECTORS, ENABLING THE USE OF STANDARD VECTOR CALCULUS. THE KRONECKER PRODUCT PLAYS A PIVOTAL ROLE IN EXPRESSING DERIVATIVES OF VECTORIZED MATRIX FUNCTIONS. THESE TOOLS ALLOW THE REPRESENTATION OF COMPLEX DERIVATIVES IN COMPACT FORMS AMENABLE TO NUMERICAL COMPUTATION.

MATRIX DIFFERENTIAL IDENTITIES

SEVERAL MATRIX IDENTITIES FACILITATE DIFFERENTIATION, SUCH AS THE DERIVATIVE OF THE INVERSE MATRIX, DETERMINANT, AND MATRIX SQUARE ROOT. THESE IDENTITIES ARE ESSENTIAL FOR DERIVING ESTIMATORS AND LIKELIHOOD FUNCTIONS INVOLVING MATRIX PARAMETERS.

NUMERICAL IMPLEMENTATION AND SOFTWARE

EFFICIENT NUMERICAL IMPLEMENTATION OF MATRIX DIFFERENTIAL CALCULUS IS CRITICAL FOR PRACTICAL APPLICATIONS. STATISTICAL AND ECONOMETRIC SOFTWARE PACKAGES OFTEN INCORPORATE MATRIX CALCULUS ROUTINES TO AUTOMATE DERIVATIVE COMPUTATIONS, IMPROVING THE SPEED AND ACCURACY OF ESTIMATION PROCEDURES.

- UTILIZING SYMBOLIC COMPUTATION TOOLS FOR MATRIX DERIVATIVES
- IMPLEMENTING CUSTOM GRADIENT AND HESSIAN FUNCTIONS
- OPTIMIZING LARGE-SCALE MATRIX COMPUTATIONS WITH SPARSE AND STRUCTURED MATRICES

FREQUENTLY ASKED QUESTIONS

WHAT IS MATRIX DIFFERENTIAL CALCULUS AND WHY IS IT IMPORTANT IN STATISTICS AND ECONOMETRICS?

MATRIX DIFFERENTIAL CALCULUS IS A BRANCH OF MATHEMATICS THAT DEALS WITH DERIVATIVES OF FUNCTIONS INVOLVING MATRICES. IT IS IMPORTANT IN STATISTICS AND ECONOMETRICS BECAUSE MANY MODELS AND ESTIMATORS CAN BE EXPRESSED IN MATRIX FORM, AND MATRIX CALCULUS PROVIDES EFFICIENT TOOLS FOR DERIVING GRADIENTS, HESSIANS, AND OTHER DERIVATIVES NECESSARY FOR OPTIMIZATION, INFERENCE, AND SENSITIVITY ANALYSIS.

HOW DO YOU COMPUTE THE DERIVATIVE OF A MATRIX-VALUED FUNCTION WITH RESPECT TO A MATRIX ARGUMENT?

TO COMPUTE THE DERIVATIVE OF A MATRIX-VALUED FUNCTION WITH RESPECT TO A MATRIX ARGUMENT, YOU TYPICALLY USE THE CONCEPT OF THE MATRIX DIFFERENTIAL AND VECTORIZATION (vec) OPERATOR. THE DERIVATIVE CAN BE REPRESENTED AS A JACOBIAN MATRIX MAPPING THE VECTORIZED INPUT MATRIX TO THE VECTORIZED OUTPUT MATRIX. RULES SUCH AS THE PRODUCT RULE, CHAIN RULE, AND PROPERTIES OF KRONECKER PRODUCTS ARE APPLIED TO FIND THE DERIVATIVE.

WHAT IS THE ROLE OF THE KRONECKER PRODUCT IN MATRIX DIFFERENTIAL CALCULUS?

THE KRONECKER PRODUCT PLAYS A CRUCIAL ROLE IN MATRIX DIFFERENTIAL CALCULUS BY SIMPLIFYING EXPRESSIONS INVOLVING DERIVATIVES OF MATRIX FUNCTIONS. IT ALLOWS REPRESENTATION OF DERIVATIVES AND VECTORIZATION OPERATIONS COMPACTLY, FACILITATING THE MANIPULATION AND COMPUTATION OF GRADIENTS AND HESSIANS IN MULTIVARIATE STATISTICAL AND ECONOMETRIC MODELS.

How is matrix differential calculus applied in maximum likelihood estimation (MLE) in econometrics?

In MLE, matrix differential calculus is used to derive score functions (gradients) and information matrices (Hessians) when model parameters are matrices or involve matrix operations. This enables efficient computation and optimization of likelihood functions in complex models such as multivariate regression, time series, and structural equation models.

What are some common matrix calculus rules used in deriving estimators in statistics?

Common rules include the product rule, chain rule, derivative of trace functions, and derivatives involving the inverse and determinant of matrices. For example, the derivative of the trace of a product of matrices and the derivative of the log-determinant function are frequently used in deriving estimators and test statistics.

Can you explain the derivative of the log-determinant function and its significance in econometrics?

The derivative of the log-determinant of a positive definite matrix A with respect to A is the inverse of A (i.e., $\frac{d}{dA} \log|A| = A^{-1}$). This result is significant in econometrics because log-determinant terms appear in likelihood functions of multivariate normal distributions and covariance matrix estimation, facilitating gradient-based optimization methods.

How does matrix differential calculus facilitate the derivation of the generalized least squares (GLS) estimator?

Matrix differential calculus allows concise derivation of the GLS estimator by differentiating the objective function with respect to the parameter vector or matrix. Using matrix derivatives, one can efficiently solve for the estimator by setting the gradient to zero, especially when dealing with covariance matrices and weighting matrices in GLS.

What software tools support matrix differential calculus for applications in statistics and econometrics?

Software tools such as MATLAB, R (with packages like 'matrixcalc' and 'numDeriv'), Python (with libraries like NumPy, SciPy, and automatic differentiation tools such as JAX or Autograd), and Mathematica support matrix differential calculus. These tools help perform symbolic and numerical matrix derivatives, enabling practical applications in statistical and econometric modeling.

Additional Resources

1. *Matrix Differential Calculus with Applications in Statistics and Econometrics* by Jan R. Magnus and Heinz Neudecker

This comprehensive text introduces the fundamentals of matrix differential calculus and its applications in statistics and econometrics. It covers topics such as derivatives of matrix functions, vectorization, and the use of Kronecker products. The book is particularly useful for researchers and students looking to deepen their understanding of matrix calculus in multivariate statistical analysis and econometric modeling.

2. *Matrix Algebra Useful for Statistics* by Shayle R. Searle

Searle's book provides a clear and concise introduction to matrix algebra with an emphasis on statistical applications. It explains matrix operations, differentiation, and their role in linear models and multivariate statistics. The text is accessible to readers with a basic understanding of linear algebra and is widely used in econometrics and statistics courses.

3. *MATRIX CALCULUS AND ZERO-ONE MATRICES: STATISTICAL AND ECONOMETRIC APPLICATIONS* BY JAN R. MAGNUS

THIS BOOK FOCUSES ON MATRIX CALCULUS TECHNIQUES INVOLVING ZERO-ONE MATRICES, WHICH FREQUENTLY APPEAR IN ECONOMETRIC AND STATISTICAL MODELS. IT BLENDS THEORETICAL DEVELOPMENT WITH PRACTICAL EXAMPLES, OFFERING INSIGHTS INTO THE MANIPULATION AND DIFFERENTIATION OF MATRIX FUNCTIONS. THE COVERAGE INCLUDES APPLICATIONS IN HYPOTHESIS TESTING AND ESTIMATION THEORY.

4. *MATRIX ALGEBRA AND ITS APPLICATIONS TO STATISTICS AND ECONOMETRICS* BY CALYAMPUDI RADHAKRISHNA RAO

RAO'S CLASSIC TEXT BRIDGES MATRIX ALGEBRA AND ITS APPLICATION IN STATISTICAL THEORY AND ECONOMETRICS. THE BOOK PROVIDES A THOROUGH TREATMENT OF MATRIX OPERATIONS, QUADRATIC FORMS, AND THEIR DERIVATIVES, ESSENTIAL FOR UNDERSTANDING ESTIMATION AND INFERENCE IN MULTIVARIATE MODELS. IT IS A FOUNDATIONAL RESOURCE FOR ADVANCED STUDENTS AND RESEARCHERS.

5. *APPLIED MATRIX ALGEBRA IN THE STATISTICAL SCIENCES* BY GEORGE A. F. SEBER

SEBER'S BOOK OFFERS AN APPLIED APPROACH TO MATRIX ALGEBRA, HIGHLIGHTING ITS RELEVANCE IN STATISTICAL COMPUTATIONS AND ECONOMETRIC ANALYSIS. IT INTRODUCES MATRIX DIFFERENTIAL CALCULUS TOOLS NECESSARY FOR MAXIMUM LIKELIHOOD ESTIMATION AND LINEAR MODEL THEORY. THE CLEAR EXPOSITION MAKES IT SUITABLE FOR PRACTITIONERS AND ACADEMICS ALIKE.

6. *MATRIX DIFFERENTIAL CALCULUS WITH APPLICATIONS TO ECONOMETRICS AND STATISTICS* BY JAN R. MAGNUS

A FOCUSED TEXT THAT DELVES INTO THE COMPUTATION OF DERIVATIVES OF MATRIX-VALUED FUNCTIONS WITH DIRECT IMPLICATIONS FOR ECONOMETRIC THEORY. IT PRESENTS SYSTEMATIC METHODS FOR DIFFERENTIATION, INCLUDING THE USE OF VECTORIZATION AND MATRIX OPERATORS. THE BOOK IS IDEAL FOR THOSE DEVELOPING OR UNDERSTANDING ECONOMETRIC MODELS INVOLVING COMPLEX MATRIX FUNCTIONS.

7. *MATRIX METHODS IN STATISTICS AND ECONOMETRICS* BY DONALD A. BERRY AND KENNETH W. JENNRICH

THIS BOOK EXPLORES MATRIX TECHNIQUES ESSENTIAL FOR MODERN STATISTICAL THEORY AND ECONOMETRIC PRACTICE. IT COVERS MATRIX DIFFERENTIATION, SPECTRAL DECOMPOSITION, AND THEIR USE IN ESTIMATION AND HYPOTHESIS TESTING. THE TEXT IS FILLED WITH EXAMPLES THAT DEMONSTRATE PRACTICAL APPLICATIONS IN DATA ANALYSIS.

8. *MATRIX ALGEBRA FOR APPLIED ECONOMETRICS* BY KEVIN SHEPPARD

SHEPPARD'S BOOK IS DESIGNED TO EQUIP ECONOMISTS WITH THE MATRIX ALGEBRA SKILLS NECESSARY FOR APPLIED ECONOMETRIC ANALYSIS. IT INCLUDES SECTIONS ON MATRIX CALCULUS THAT FACILITATE UNDERSTANDING OF GRADIENT AND HESSIAN COMPUTATIONS IN ECONOMETRIC OPTIMIZATION PROBLEMS. THE TEXT IS PRACTICAL, WITH EXERCISES THAT REINFORCE THEORETICAL CONCEPTS.

9. *MATRIX CALCULUS AND ECONOMETRIC APPLICATIONS* BY WILLIAM H. GREENE

GREENE'S WORK INTEGRATES MATRIX CALCULUS TECHNIQUES WITH ECONOMETRIC THEORY, EMPHASIZING THEIR UTILITY IN ESTIMATION AND INFERENCE. THE BOOK PROVIDES DETAILED DERIVATIONS AND APPLICATIONS RELATED TO MAXIMUM LIKELIHOOD AND GENERALIZED METHOD OF MOMENTS ESTIMATORS. IT IS A VALUABLE RESOURCE FOR GRADUATE STUDENTS AND PROFESSIONALS IN ECONOMETRICS.

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