

¹ FSML – A Modern Fortran Statistics and Machine Learning Library

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Software

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⁵ Summary

⁶ FSML is a modern Fortran statistics and machine learning library suitable for contemporary research problems and teaching. It includes procedures for basic statistics, hypothesis tests, linear and non-linear methods, and statistical distribution functions.

⁹ Statement of Need

¹⁰ The advances in computing technology over the past two decades have expanded the practical scope of statistics and allowed the widespread use of machine learning (ML). This also ¹¹ transformed research practices and enhanced predictive modelling across many disciplines, ¹² including Earth sciences ([Boateng & Mutz, 2023](#)), operational weather forecasting ([Lang et al., 2024](#)), and more.

¹³ Fortran is a well-established general purpose programming language that is commonly adopted ¹⁴ in science due to its stability, reliability, performance, and array functionality. It is widely used ¹⁵ for parallelised high-performance computing and numerical modelling (e.g., [Giorgetta et al., 2018](#)). ¹⁶ The same strengths make it suitable for computationally demanding ML procedures ¹⁷ and data-driven predictions. However, despite Fortran's long history in data-driven prediction ¹⁸ and ML (e.g., [Breiman, 2001](#); [Gutmann et al., 2022](#); [Tomassetti et al., 2009](#)), it has not been ¹⁹ as widely adopted in these fields as other languages and lacks well documented, accessible ²⁰ toolkits for statistics and classic ML.

²¹ Although projects like Neural-Fortran ([Curcic, 2019](#)), ATHENA ([Taylor, 2024](#)), and FStats ²² cover some important procedures for deep-learning and classic statistics, the Fortran statistics ²³ and ML ecosystem remains relatively small. This potentially deters from the use of Fortran, ²⁴ which is already perceived as less accessible than other popular languages due to 1) the lack ²⁵ of familiarity with modern Fortran features, which is exacerbated by stagnating adoption of ²⁶ Fortran at universities, and 2) shortcomings that are currently being addressed by Fortran-lang ²⁷ community projects ([Kedward et al., 2022](#)).

²⁸ FSML (Fortran Statistics and Machine Learning) purposefully integrates these projects: It uses ²⁹ [stdlib](#) for linear algebra, leverages [fpm](#) for easier building and distribution, and is developed to ³⁰ support compilation with the interactive [LFortran](#) compiler in addition to GFortran. As such, ³¹ it builds on recent community efforts and addresses two needs:

- ³² 1. It adds to the modern Fortran statistics and ML software ecosystem; a richer ecosystem ³³ makes Fortran a more attractive choice as a well-established, robust, high-performance ³⁴ language.
- ³⁵ 2. The use of fpm, the support of free open-source compilers, the extensive documentation, ³⁶ and its permissive license (MIT) facilitate its early adoption and integration into various ³⁷ applications.

39 statistics and ML projects by students, early career researchers, and teachers. It can
 40 thus promote the adoption of Fortran.

41 Software Description

42 Scope

43 FSML consists of a set of accessible and well-documented statistics and ML procedures, suitable
 44 for many contemporary research problems and teaching. These procedures are subdivided into
 45 five categories:

- 46 ▪ DST: Statistical distribution functions (e.g., the probability density, cumulative distribution,
 47 and quantile functions of the Student's t and generalised Pareto distributions).
- 48 ▪ STS: Basic statistics for describing and understanding data (e.g., mean, variance,
 49 correlation).
- 50 ▪ TST: Parametric and non-parametric hypothesis tests (e.g., analysis of variance,
 51 Mann–Whitney U).
- 52 ▪ LIN: Statistical procedures relying heavily on linear algebra (e.g., principal component
 53 analysis, ridge regression, linear discriminant analysis).
- 54 ▪ NLP: Non-linear and algorithmic procedures (e.g., k-means clustering).

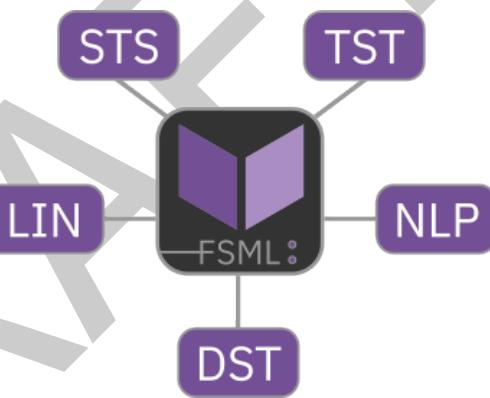


Figure 1: FSML has five thematic modules: Basic statistics (STS), hypothesis tests (TST), linear procedures (LIN), non-linear procedures (NLP), and statistical distribution functions (DST).

55 FSML has minimal requirements. It uses Fortran 2008 features, Fortran-lang stdlib for linear
 56 algebra, and fpm for easy building and distribution.

57 **Note:** At the time of publication, LFortran does not reliably compile stdlib. Therefore, early
 58 users of FSML are advised to use GFortran.

59 Documentation

60 The FSML handbook is hosted on fsml.mutz.science and can be re-generated from its source
 61 files. It includes a detailed, example-rich documentation of the covered procedures, as well as
 62 installation instructions and information for contributors.

63 Examples

64 The examples below demonstrate the use of FSML interfaces, using double precision (dp):

- 65 ▪ statistical distribution functions:

```

! exponential distribution probability density function
! with x=0.8 and lambda=0.5
fx = fsml_exp_pdf(0.8_dp, lambda=0.5_dp)
! generalised Pareto cumulative distribution function
! with modified shape (xi) and location (mu) parameters
fx = fsml_gpd_cdf(1.9_dp, xi=1.2_dp, mu=0.6_dp)

66   ▪ sample statistics and dependency measures:
      ! mean of vector x
      mean = fsml_mean(x)
      ! sample standard deviation of vector x
      std = fsml_std(x, ddf=1.0_dp)
      ! Pearson correlation coefficient for vectors x1 and x2
      pcc = fsml_pcc(x1, x2)

67   ▪ hypothesis tests:
      ! two-sample t-test for unequal variances (Welch's t-test);
      ! returns test statistic (t), degrees of freedom (df), and p
      call fsml_ttest_2sample(x1, x2, t, df, p, eq_var=.false.)
      ! one-way ANOVA on a rank-2 array (x2d);
      ! returns f-statistic (f), degrees of freedom (df1, df2) and p
      call fsml_anova_1way(x2d, f, df1, df2, p)

68   ▪ multiple linear ridge regression:
      ! ridge regression for 100 data points, 5 variables, and lambda=0.2;
      ! returns y intercept (b0), regression coefficients (b), and R^2 (rsq)
      call fsml_ridge(x, y, 100, 5, 0.2_dp, b0, b, rsq)

69   FSML's repository and handbook includes examples for every public interface.

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70 Past and Ongoing FSML Projects

71 The FSML procedures for clustering and linear discriminant analysis were reworked from the
 72 code used for climate pattern detection and explanation (Mutz et al., 2018; Mutz & Ehlers,
 73 2019). FSML's empirical orthogonal functions and analysis of variance were used in Mutz
 74 (2025). FSML's distribution functions are currently used for modelling climate extremes.

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 77 stdlib, and LFortran), as well as the always helpful discussions the with the same community on
 78 [Fortran Discourse](#) and GitHub. I thank the editor (Jack Atkinson) and reviewers (Ivan Pribec
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80 References

- 81 Boateng, D., & Mutz, S. G. (2023). pyESDv1.0.1: An open-source python framework for
 82 empirical-statistical downscaling of climate information. *Geoscientific Model Development*,
 83 16(22), 6479–6514. <https://doi.org/10.5194/gmd-16-6479-2023>
- 84 Breiman, L. (2001). Random forests. *Machine Learning*, 45(1), 5–32. <https://doi.org/10.1023/A:1010933404324>

- 86 Curcic, M. (2019). A parallel fortran framework for neural networks and deep learning.
87 *SIGPLAN Fortran Forum*, 38(1), 4–21. <https://doi.org/10.1145/3323057.3323059>
- 88 Giorgetta, M. A., Brokopf, R., Crueger, T., Esch, M., Fiedler, S., Helmert, J., Hohenegger,
89 C., Kornblueh, L., Köhler, M., Manzini, E., Mauritsen, T., Nam, C., Raddatz, T., Rast,
90 S., Reinert, D., Sakradzija, M., Schmidt, H., Schneck, R., Schnur, R., ... Stevens, B.
91 (2018). ICON-a, the atmosphere component of the ICON earth system model: I. Model
92 description. *Journal of Advances in Modeling Earth Systems*, 10(7), 1613–1637. <https://doi.org/10.1029/2017MS001242>
- 94 Gutmann, E. D., Hamman, Joseph. J., Clark, M. P., Eidhammer, T., Wood, A. W., &
95 Arnold, J. R. (2022). En-GARD: A statistical downscaling framework to produce and test
96 large ensembles of climate projections. *Journal of Hydrometeorology*, 23(10), 1545–1561.
97 <https://doi.org/10.1175/JHM-D-21-0142.1>
- 98 Kedward, L. J., Aradi, B., Čertík, O., Curcic, M., Ehlert, S., Engel, P., Goswami, R., Hirsch,
99 M., Lozada-Blanco, A., Magnin, V., Markus, A., Pagone, E., Pribec, I., Richardson, B.,
100 Snyder, H., Urban, J., & Vandenplas, J. (2022). The state of fortran. *Computing in
101 Science & Engineering*, 24(2), 63–72. <https://doi.org/10.1109/MCSE.2022.3159862>
- 102 Lang, S., Alexe, M., Chantry, M., Dramsch, J., Pinault, F., Raoult, B., Clare, M. C., Lessig,
103 C., Maier-Gerber, M., Magnusson, L., & others. (2024). AIFS-ECMWF's data-driven
104 forecasting system. *arXiv Preprint arXiv:2406.01465*. <https://doi.org/10.48550/arXiv.2406.01465>
- 106 Mutz, S. G. (2025). The effect of high-mountain asia topography on northern hemisphere
107 atmospheric flow. *EGU General Assembly 2025, Vienna, Austria, 27 Apr–2 May 2025*,
108 *EGU25-7283*. <https://doi.org/10.5194/egusphere-egu25-7283>
- 109 Mutz, S. G., & Ehlers, T. A. (2019). Detection and explanation of spatiotemporal patterns
110 in late cenozoic palaeoclimate change relevant to earth surface processes. *Earth Surface
111 Dynamics*, 7(3), 663–679. <https://doi.org/10.5194/esurf-7-663-2019>
- 112 Mutz, S. G., Ehlers, T. A., Werner, M., Lohmann, G., Stepanek, C., & Li, J. (2018). Estimates
113 of late cenozoic climate change relevant to earth surface processes in tectonically active orogenes.
114 *Earth Surface Dynamics*, 6(2), 271–301. <https://doi.org/10.5194/esurf-6-271-2018>
- 115 Taylor, N. T. (2024). ATHENA: A fortran package for neural networks. *Journal of Open
116 Source Software*, 9(99), 6492. <https://doi.org/10.21105/joss.06492>
- 117 Tomassetti, B., Verdecchia, M., & Giorgi, F. (2009). NN5: A neural network based approach
118 for the downscaling of precipitation fields – model description and preliminary results.
119 *Journal of Hydrology*, 367(1), 14–26. <https://doi.org/10.1016/j.jhydrol.2008.12.017>