



Universiteit
Leiden
The Netherlands

E-values for anytime-valid inference with exponential families

Hao, Y.

Citation

Hao, Y. (2025, February 18). *E-values for anytime-valid inference with exponential families*. Retrieved from <https://hdl.handle.net/1887/4195433>

Version: Publisher's Version

License: [Licence agreement concerning inclusion of doctoral thesis in the Institutional Repository of the University of Leiden](#)

Downloaded from: <https://hdl.handle.net/1887/4195433>

Note: To cite this publication please use the final published version (if applicable).

E-Values for Anytime-Valid Inference with Exponential Families

Proefschrift

ter verkrijging van
de graad van doctor aan de Universiteit Leiden,
op gezag van rector magnificus prof.dr.ir. H. Bijl,
volgens besluit van het college voor promoties
te verdedigen op dinsdag 18 februari 2025
klokke 14:30 uur

door

Yunda Hao
geboren te Cangzhou, Hebei Province, China
in 1994

Promotores:

Prof.dr. P.D. Grünwald (Universiteit Leiden and Centrum Wiskunde & Informatica)
Dr. A. Ly (Centrum Wiskunde & Informatica)

Promotiecommissie:

Prof.dr. T. Dickhaus (Bremen University)
Dr. Z. Ren (University of Pennsylvania)
Dr. N.W. Koning (Erasmus University Rotterdam)
Prof.dr.ir. G.L.A. Derkx
Prof.dr. M. Fiocco

The research in this dissertation was funded by the China Scholarship Council (Grant No. 202006280045). The research was performed at Centrum Wiskunde & Informatica (CWI) in Amsterdam, the national research institute for mathematics and computer science in the Netherlands.

Copyright © 2024 Yunda Hao

The cover is from <https://pixabay.com/>.



Universiteit
Leiden
The Netherlands



Centrum Wiskunde & Informatica

Contents

1	Introduction	1
1.1	Hypothesis testing	1
1.2	Anytime-valid tests: e-value, e-process	4
1.3	Preliminary knowledge: RIPr and e-power	8
1.4	Preliminary knowledge: Exponential family	9
1.5	Outline	10
1.A	More exponential family preliminaries	14
2	Optimal E-Values for Exponential Families: the Simple Case	17
2.1	Introduction	17
2.2	Existence of Simple Local E-Variables	24
2.3	Existence of Simple Global E-Variables (Main Result)	25
2.4	Examples	28
2.5	Proof of Theorem 1	38
2.6	Conclusion and Future Work	40
2.A	Details for Section 2.4.4	41
3	E-Values for Exponential Families: the General Case	43
3.1	Introduction	43
3.2	The Gaussian Location Family	50
3.3	Multivariate exponential family	57
3.4	Proofs for Section 3.2	65
3.5	Proofs for Section 3.3	69
3.6	Implications, Conclusions and Future Work	72
3.7	Acknowledgements	74
3.A	Proofs underlying Theorem 2 and 3: the Gaussian Case	75

Contents

3.B	Proofs underlying Theorem 4 and 5: the general case	77
3.C	Proofs for Section 3.6	89
3.D	Additional Details for Section 3.3: checking UI and plug-in Regularity Conditions for Example Families	90
4	E-values for k-Sample Tests With Exponential Families	95
4.1	Introduction	95
4.2	The Four Types of E-variables	101
4.3	Growth Rate Comparison of Our E-variables	104
4.4	Growth Rate Comparison for Specific Exponential Families	106
4.5	Simulations to Approximate the RI _{Pr}	109
4.6	Conclusion and Future Work	110
4.A	Application in Practice: k Separate I.I.D. Data Streams	111
4.B	Proofs for Section 4.2	112
4.C	Proofs for Section 4.3	116
4.D	Proofs for Section 4.4	123
4.E	Graphical Depiction of RI _{Pr} -Approximation and Convergence of Li's Algorithm	125
5	Growth-Optimal E-Variables and an extension to the multivariate Csiszár-Sanov-Chernoff Theorem	133
5.1	Introduction	133
5.2	Convex M_1	140
5.3	Surrounding M_1	144
5.4	Asymptotic expression of growth rate and regret	152
5.5	Proof of Lemma 9 and further discussion of Theorem 11	155
5.6	Discussion, Conclusion, Future Work	157
6	Discussion	159
6.1	Well-specified model tests	159
6.2	k -sample tests	160
6.3	GROW e-variables and concentration inequality	161
Bibliography		163
List of publications		171
Samenvatting		173

Contents

Summary	177
Acknowledgements	183
Curriculum Vitae	185

Contents
