



Bayesian Item Response Modeling in R with brms and Stan

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Abstract

Item response theory (IRT) is widely applied in the human sciences to model persons' responses on a set of items measuring one or more latent constructs. While several R packages have been developed that implement IRT models, they tend to be restricted to respective pre-specified classes of models. Further, most implementations are frequentist while the availability of Bayesian methods remains comparably limited. I demonstrate how to use the R package `brms` together with the probabilistic programming language `Stan` to specify and fit a wide range of Bayesian IRT models using flexible and intuitive multilevel formula syntax. Further, item and person parameters can be related in both a linear or non-linear manner. Various distributions for categorical, ordinal, and continuous responses are supported. Users may even define their own custom response distribution for use in the presented framework. Common IRT model classes that can be specified natively in the presented framework include 1PL and 2PL logistic models optionally also containing guessing parameters, graded response and partial credit ordinal models, as well as drift diffusion models of response times coupled with binary decisions. Posterior distributions of item and person parameters can be conveniently extracted and post-processed. Model fit can be evaluated and compared using Bayes factors and efficient cross-validation procedures.

Keywords: item response theory, Bayesian statistics, R, Stan, `brms`.

1. Introduction

Item response theory (IRT) is widely applied in the human sciences to model persons' responses on a set of items measuring one or more latent constructs (for a comprehensive introduction see Lord 1980; Embretson and Reise 2000; Van der Linden and Hambleton 1997). Due to its flexibility compared to classical test theory, IRT provides the formal statistical basis for most modern psychological measurement. The best known IRT models are likely

Bayesian Item Response Modeling Bayesian Item Response Modeling

Yanlin Jiang



Bayesian Item Response Modeling Bayesian Item Response Modeling:

Bayesian Item Response Modeling Jean-Paul Fox, 2010-05-19 The modeling of item response data is governed by item response theory also referred to as modern test theory The field of inquiry of item response theory has become very large and shows the enormous progress that has been made The mainstream literature is focused on frequentist statistical methods for estimating model parameters and evaluating model fit However the Bayesian methodology has shown great potential particularly for making further improvements in the statistical modeling process The Bayesian approach has two important features that make it attractive for modeling item response data First it enables the possibility of incorporating nondata information beyond the observed responses into the analysis The Bayesian methodology is also very clear about how additional information can be used Second the Bayesian approach comes with powerful simulation based estimation methods These methods make it possible to handle all kinds of priors and data generating models One of my motives for writing this book is to give an introduction to the Bayesian methodology for modeling and analyzing item response data A Bayesian counterpart is presented to the many popular item response theory books e.g. Baker and Kim 2004 De Boeck and Wilson 2004 Hambleton and Swaminathan 1985 van der Linden and Hambleton 1997 that are mainly or completely focused on frequentist methods The usefulness of the Bayesian methodology is illustrated by discussing and applying a range of Bayesian item response models

Bayesian Item Response Theory: Methods and Applications Yang Liu, 2019 Item response theory IRT models play a critical role in psychometric studies for the design and analysis of examinations IRT models mainly consider the relationship among the correctness of items individual's latent ability difficulty of each item and other potential factors such as guessing In this dissertation we develop Bayesian modeling methods and model selection techniques under the IRT model framework For Bayesian model comparison the Bayes factor is a widely used tool which requires computation of the marginal likelihoods For complex models such as the IRT models the marginal likelihoods are not analytically available There are a variety of Monte Carlo methods for estimating or computing the marginal likelihoods though some of them may not be feasible for IRT models due to the high dimensionality of the parameter space We review several different Monte Carlo methods for marginal likelihood computation under classic IRT models develop the best implementation of these methods for the IRT models and apply these methods to a real dataset for comparison of the classic one parameter IRT model and two parameter IRT model With increasing availability of computerized testing observations are often collected at irregular and variable time points We adopt a dynamic IRT model based on the one parameter IRT model to accommodate this data structure A hierarchical layer on the dynamic IRT model is built to capture the relationship between the growth factor and the characteristics of individuals We use the Bayes factor to perform variable selection on the covariates linked to the growth and develop a Monte Carlo approach to compute the Bayes factors for all model pairs using a single Markov chain Monte Carlo MCMC output We also show the model selection consistency of the Bayes factor under certain conditions Additionally

to allow more flexibility we propose a nonparametric model and embed a monotone shape constraint on the mean latent growth trend Further we develop a partially collapsed Gibbs sampling algorithm coupled with a reversible jump MCMC technique to sample the dimension varying parameters from their corresponding posterior distribution **Bayesian**

Analysis of Item Response Theory Models Using SAS Clement A. Stone,Xiaowen Zhu,2015-03-01 Written especially for psychometricians scale developers and practitioners interested in applications of Bayesian estimation and model checking of item response theory IRT models this book teaches you how to accomplish all of this with the SAS MCMC Procedure Because of its tutorial structure Bayesian Analysis of Item Response Theory Models Using SAS will be of immediate practical use to SAS users with some introductory background in IRT models and the Bayesian paradigm Working through this book s examples you will learn how to write the PROC MCMC programming code to estimate various simple and more complex IRT models including the choice and specification of prior distributions specification of the likelihood model and interpretation of results Specifically you will learn PROC MCMC programming code for estimating particular models and ways to interpret results that illustrate convergence diagnostics and inferences for parameters as well as results that can be used by scale developers for example the plotting of item response functions In addition you will learn how to compare competing IRT models for an application as well as evaluate the fit of models with the use of posterior predictive model checking methods Numerous programs for conducting these analyses are provided and annotated so that you can easily modify them for your applications *Handbook of Item Response Theory* Wim J. van der Linden,2018-02-19 Drawing on the work of 75

internationally acclaimed experts in the field *Handbook of Item Response Theory* Three Volume Set presents all major item response models classical and modern statistical tools used in item response theory IRT and major areas of applications of IRT in educational and psychological testing medical diagnosis of patient reported outcomes and marketing research It also covers CRAN packages WinBUGS Bilog MG Multilog Parscale IRTPRO Mplus GLLAMM Latent Gold and numerous other software tools A full update of editor Wim J van der Linden and Ronald K Hambleton s classic *Handbook of Modern Item Response Theory* this handbook has been expanded from 28 chapters to 85 chapters in three volumes The three volumes are thoroughly edited and cross referenced with uniform notation format and pedagogical principles across all chapters Each chapter is self contained and deals with the latest developments in IRT **Bayesian Analysis of Item Response Theory**

and Its Applications to Longitudinal Education Data Abhisek Saha,2016 Inferences on ability in item response theory IRT have been mainly based on item responses while response time is often ignored This is a loss of information especially with the advent of computerized tests Most of the IRT models may not apply to these modern computerized tests as they still suffer from at least one of the three problems local independence randomized item and individually varying test dates due to the flexibility and complex designs of computerized adaptive tests In Chapter 2 we propose a new class of state space models namely dynamic item responses and response times models DIR RT models which conjointly model response time with time

series of dichotomous responses It aims to improve the accuracy of ability estimation via auxiliary information from response time A simulation study is conducted to ensure correctness of proposed sampling schemes to estimate parameters whereas an empirical study is conducted using MetaMetrics datasets to demonstrate its implications in practice In Chapter 3 we have investigated the difficulty in implementing the standard model diagnostic methods while comparing two popular response time models i e monotone and inverted U shape A new variant of conditional deviance information criterion DIC is proposed and some simulation studies are conducted to check its performance The results of model comparison support the inverted U shaped model as discussed in Chapter 1 which can better capture examinees behaviors and psychology in exams The estimates of ability via Dynamic Item Response models DIR or DIR RT model often are non monotonic and zig zagged because of irregularly spaced time points though the inherent mean ability growth process is monotonic and smooth Also the parametric assumption of ability process may not be always exact To have more flexible yet smooth and monotonic estimates of ability we propose a semi parametric dynamic item response model and study the robustness of the proposed model Finally as every student s growth is different from others it may be of importance to identify groups of fast learners from slow learners The growth curves are clustered into distinct groups based on learning rates A spline derivative based clustering method is suggested in light of its efficacy on some simulated data in Chapter 5 as part of future works

BAYESIAN MODEL CHECKING METHODS FOR DICHOTOMOUS ITEM RESPONSE THEORY AND TESTLET MODELS Adam Combs, OhioLINK Electronic Theses and Dissertations Center, 2014 The predominant model checking method used in Bayesian item response theory IRT models has been the posterior predictive PP method In recent years two new Bayesian model checking methods have been proposed that may be used as alternatives to the PP method We refer to these as the prior predictive posterior simulation PPPS method of Dey et al 1998 and the pivotal discrepancy measure PDM method of Johnson 2007 These methods have shown to be effective in other Bayesian models but have never been implemented with Bayesian IRT models It is of practical interest to see if either of these two new methods will perform better than the PP method in assessing aspects of fit in an IRT model setting In this dissertation we compared the effectiveness of the PPPS and PDM model checking methods with the PP method in evaluating person fit in two parameter normal ogive 2PN IRT models and overall model goodness of fit in 2PN testlet models Two simulation studies were performed The first study explored the performance of each method PP PPPS and PDM in assessing person fit or the goodness of fit of an individual s set of test answers with the assumed Bayesian 2PN IRT model Several classical person fit measures were employed under each method We also introduced using the sum of squared Bayesian latent residuals as a person fit measure Four different types of person miss fit were taken from the literature and response data sets were simulated with certain examinee s responses following these violations We found that for most of the measures the PPPS and PDM methods outperformed the PP method in detecting the examinee s response patterns simulated to be aberrant under the model In particular the sum of squared

Bayesian latent residuals showed to be a very effective measure under the PPPS method. The second simulation study compares the performance of the PP method and the PPPS method in assessing the overall goodness of fit of a Bayesian 2PN IRT model fitted to data generated under a Bayesian 2PN testlet model with equal variance across testlets. Under the PP method we used three goodness of fit measures based on biserial correlations that were previously employed for checking the goodness of fit of a three parameter logistic 3PL IRT model to 3PL testlet data. For use under the PPPS method we introduced three new goodness of fit measures which are calculated from posterior values of the item discrimination parameters. Data sets were simulated under four different values of testlet variance ranging from very low to fairly high. Looking at the detection rates under the PP method we saw that the measures performed very poorly in detecting a lack of fit of the 2PN IRT model for all data values of testlet variance. The detection rates of the new measures under the PPPS method showed to be higher than those under the PP method. However the measures under the PPPS method only showed descent power in detecting lack of fit for large values of data generating testlet variance.

The Wiley Handbook of Psychometric Testing Paul Irwing, Tom Booth, David J. Hughes, 2018-02-12. A must have resource for researchers, practitioners and advanced students interested or involved in psychometric testing. Over the past hundred years psychometric testing has proved to be a valuable tool for measuring personality, mental ability, attitudes and much more. The word psychometrics can be translated as mental measurement, however the implication that psychometrics as a field is confined to psychology is highly misleading. Scientists and practitioners from virtually every conceivable discipline now use and analyze data collected from questionnaires, scales and tests developed from psychometric principles and the field is vibrant with new and useful methods and approaches. This handbook brings together contributions from leading psychometricians in a diverse array of fields around the globe. Each provides accessible and practical information about their specialist area in a three step format covering historical and standard approaches, innovative issues and techniques and practical guidance on how to apply the methods discussed. Throughout real world examples help to illustrate and clarify key aspects of the topics covered. The aim is to fill a gap for information about psychometric testing that is neither too basic nor too technical and specialized and will enable researchers, practitioners and graduate students to expand their knowledge and skills in the area. Provides comprehensive coverage of the field of psychometric testing from designing a test through writing items to constructing and evaluating scales. Takes a practical approach addressing real issues faced by practitioners and researchers. Provides basic and accessible mathematical and statistical foundations of all psychometric techniques discussed. Provides example software code to help readers implement the analyses discussed.

Bayesian Item Response Theory Models for Measurement Variance Anna Jozina Verhagen, 2012

Analysis of an Intelligence Dataset Nils Myszkowski, 2021-02-12. In this issue psychometrics researchers were invited to make reanalyses or extensions of a previously published dataset from a recent paper by Myszkowski and Storme (2018). The dataset analyzed consisted of responses to a multiple choice logical reasoning

nonverbal test comprising the last series of Raven's 1941 Standard Progressive Matrices. Although the original paper already proposed several modeling strategies, this issue presents new or improved procedures to study the psychometric properties of tests of this type. *Mathematical Models for Intertemporal Choice* Salvador Cruz Rambaud, Taiki Takahashi, 2021-09-30

Bayesian Randomized Item Response Modeling for Sensitive Measurements Marianna Avetisyan, 2012 **Estimation of Item Response Models Using the EM Algorithm for Finite Mixtures** David Woodruff, 1996 **Methodological Issues in Psychology and Social Sciences Research** Begoña Espejo, Marta Martín-Carbonell, Irene Checa, 2023-01-11

Bayesian Statistics and Its Applications Satyanshu K. Upadhyay, Umesh Singh, Dipak Dey, 2007 In the last two decades Bayesian Statistics has acquired immense importance and has penetrated almost every area including those where the application of statistics appeared to be a remote possibility. This volume provides both theoretical and practical insights into the subject with detailed up-to-date material on various aspects. It serves two important objectives: to offer a thorough background material for theoreticians and gives a variety of applications for applied statisticians and practitioners. Consisting of 33 chapters, it covers topics on biostatistics, econometrics, reliability, image analysis, Bayesian computation, neural networks, prior elicitation, objective Bayesian methodologies, role of randomisation in Bayesian analysis, spatial data analysis, nonparametrics, and a lot more. The book will serve as an excellent reference work for updating knowledge and for developing new methodologies in a wide variety of areas. It will become an invaluable tool for statisticians and the practitioners of Bayesian paradigm. *Bayesian Item Fit Analysis for Dichotomous Item Response Theory Models* Sandip Sinharay, Educational Testing Service. Research & Development Division, 2003 *Proceedings of the Section on Bayesian Statistical Science* American Statistical Association. Section on Bayesian Statistical Science, 1997 *Explanatory Item Response Models* Paul de Boeck, 2004-06-29 This edited volume gives a new and integrated introduction to item response models predominantly used in measurement applications in psychology, education, and other social science areas from the viewpoint of the statistical theory of generalized linear and nonlinear mixed models. The new framework allows the domain of item response models to be coordinated and broadened to emphasize their explanatory uses beyond their standard descriptive uses. The basic explanatory principle is that item responses can be modeled as a function of predictors of various kinds. The predictors can be characteristics of items, of persons, and of combinations of persons and items; observed or latent of either items or persons; and they can be continuous or latent categorical. In this way a broad range of models is generated, including a wide range of extant item response models as well as some new ones. Within this range, models with explanatory predictors are given special attention in this book, but we also discuss descriptive models. Note that the term item responses does not just refer to the traditional test data but are broadly conceived as categorical data from a repeated observations design. Hence data from studies with repeated observations, experimental designs, or with longitudinal designs may also be modelled. The book starts with a four-chapter section containing an introduction to the framework. The remaining

chapters describe models for ordered category data multilevel models models for differential item functioning multidimensional models models for local item dependency and mixture models It also includes a chapter on the statistical background and one on useful software In order to make the task easier for the reader a unified approach to notation and model description is followed throughout the chapters and a single data set is used in most examples to make it easier to see how the many models are related For all major examples computer commands from the SAS package are provided that can be used to estimate the results for each model In addition sample commands are provided for other major computer packages Paul De Boeck is Professor of Psychology at K U Leuven Belgium and Mark Wilson is Professor of Education at UC Berkeley USA They are also co editors along with Pamela Moss of a new journal entitled Measurement Interdisciplinary Research and Perspectives The chapter authors are members of a collaborative group of psychometricians and statisticians centered on K U Leuven and UC Berkeley

Estimating Parameters for Multidimensional Item Response Theory Models by MCMC Methods Yanlin Jiang, 2005 Bayesian Analysis of Item Response Models for Binary Data Atalanta Ghosh, 1996 **Bayesian Irt Models with General and Specific Traits** Yanyan Sheng, 2008 Modeling the interaction between persons and items for binary response data item response theory IRT has been found useful in a wide variety of applications Over the past decades studies have been conducted on the development and application of unidimensional as well as multidimensional IRT models However little literature exists on IRT based models that incorporate one general trait and several specific trait dimensions This book therefore proposes such models in the Bayesian hierarchical framework assesses their performances in various testing situations and further compares them with the conventional IRT models using Bayesian model choice techniques Results from the analysis suggest that the proposed models offer a better way to represent the test situations not realized in existing models The methodology and analysis should shed some light on the development of complex IRT models and the statistical procedures for parameter estimation and should be especially useful to professionals in educational and psychological measurement or anyone who may be considering utilizing IRT models for assessing persons continuous latent traits

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