

A Matrix Factorization Approach to Multiple Imputation

Knowledge Lab Team Presentation

Nandana Sengupta

(co-authors: Madeleine Udell, James Evans, Nati Srebro)

February 10, 2016

Introduction

Introduction

- ▶ Missing data arise in almost all empirical analysis.

Introduction

- ▶ Missing data arise in almost all empirical analysis.
- ▶ Distracts from main goal of study.

Introduction

- ▶ Missing data arise in almost all empirical analysis.
- ▶ Distracts from main goal of study.
- ▶ Social science

Introduction

- ▶ Missing data arise in almost all empirical analysis.
- ▶ Distracts from main goal of study.
- ▶ Social science
 - ▶ opinion surveys

Introduction

- ▶ Missing data arise in almost all empirical analysis.
- ▶ Distracts from main goal of study.
- ▶ **Social science**
 - ▶ opinion surveys
 - ▶ longitudinal surveys

Introduction

- ▶ Missing data arise in almost all empirical analysis.
- ▶ Distracts from main goal of study.
- ▶ Social science
 - ▶ opinion surveys
 - ▶ longitudinal surveys
- ▶ Ad-hoc methods

Introduction

- ▶ Missing data arise in almost all empirical analysis.
- ▶ Distracts from main goal of study.
- ▶ **Social science**
 - ▶ opinion surveys
 - ▶ longitudinal surveys
- ▶ **Ad-hoc methods**
 - ▶ Complete case analysis (fully observed rows).

Introduction

- ▶ Missing data arise in almost all empirical analysis.
- ▶ Distracts from main goal of study.
- ▶ **Social science**
 - ▶ opinion surveys
 - ▶ longitudinal surveys
- ▶ **Ad-hoc methods**
 - ▶ Complete case analysis (fully observed rows).
 - ▶ Available case analysis (fully observed columns).

Introduction

- ▶ Missing data arise in almost all empirical analysis.
- ▶ Distracts from main goal of study.
- ▶ **Social science**
 - ▶ opinion surveys
 - ▶ longitudinal surveys
- ▶ **Ad-hoc methods**
 - ▶ Complete case analysis (fully observed rows).
 - ▶ Available case analysis (fully observed columns).
 - ▶ Mean Imputation.

Introduction

- ▶ Missing data arise in almost all empirical analysis.
- ▶ Distracts from main goal of study.
- ▶ **Social science**
 - ▶ opinion surveys
 - ▶ longitudinal surveys
- ▶ **Ad-hoc methods**
 - ▶ Complete case analysis (fully observed rows).
 - ▶ Available case analysis (fully observed columns).
 - ▶ Mean Imputation.
- ▶ Concerns about validity of inferences.

Introduction

- ▶ Missing data arise in almost all empirical analysis.
- ▶ Distracts from main goal of study.
- ▶ **Social science**
 - ▶ opinion surveys
 - ▶ longitudinal surveys
- ▶ **Ad-hoc methods**
 - ▶ Complete case analysis (fully observed rows).
 - ▶ Available case analysis (fully observed columns).
 - ▶ Mean Imputation.
- ▶ Concerns about validity of inferences.
- ▶ **Types of Missing Data**

Introduction

- ▶ Missing data arise in almost all empirical analysis.
- ▶ Distracts from main goal of study.
- ▶ **Social science**
 - ▶ opinion surveys
 - ▶ longitudinal surveys
- ▶ **Ad-hoc methods**
 - ▶ Complete case analysis (fully observed rows).
 - ▶ Available case analysis (fully observed columns).
 - ▶ Mean Imputation.
- ▶ Concerns about validity of inferences.
- ▶ **Types of Missing Data**
 - ▶ Missing Completely at Random.

Introduction

- ▶ Missing data arise in almost all empirical analysis.
- ▶ Distracts from main goal of study.
- ▶ **Social science**
 - ▶ opinion surveys
 - ▶ longitudinal surveys
- ▶ **Ad-hoc methods**
 - ▶ Complete case analysis (fully observed rows).
 - ▶ Available case analysis (fully observed columns).
 - ▶ Mean Imputation.
- ▶ Concerns about validity of inferences.
- ▶ **Types of Missing Data**
 - ▶ Missing Completely at Random.
 - ▶ Missingness depends on unobservables.

Introduction

- ▶ Missing data arise in almost all empirical analysis.
- ▶ Distracts from main goal of study.
- ▶ **Social science**
 - ▶ opinion surveys
 - ▶ longitudinal surveys
- ▶ **Ad-hoc methods**
 - ▶ Complete case analysis (fully observed rows).
 - ▶ Available case analysis (fully observed columns).
 - ▶ Mean Imputation.
- ▶ Concerns about validity of inferences.
- ▶ **Types of Missing Data**
 - ▶ Missing Completely at Random.
 - ▶ Missingness depends on unobservables.
 - ▶ Missing at Random.

Multiple Imputation

Multiple Imputation

- ▶ Rubin (1976), Schafer (1998), Van Buuren et al (1999), King et al (2000, 2015)

Multiple Imputation

- ▶ Rubin (1976), Schafer (1998), Van Buuren et al (1999), King et al (2000, 2015)
- ▶ **Idea:** Analysis should reflect uncertainty inherent in imputation.

Multiple Imputation

- ▶ Rubin (1976), Schafer (1998), Van Buuren et al (1999), King et al (2000, 2015)
- ▶ **Idea:** Analysis should reflect uncertainty inherent in imputation.
- ▶ Complete data D (dimension $n \times p$), observed data D^{obs} , Missingness Matrix M

Multiple Imputation

- ▶ Rubin (1976), Schafer (1998), Van Buuren et al (1999), King et al (2000, 2015)
- ▶ **Idea:** Analysis should reflect uncertainty inherent in imputation.
- ▶ Complete data D (dimension $n \times p$), observed data D^{obs} , Missingness Matrix M
- ▶ **Assumption 1:** Missing at Random: $P(M|D) = P(M|D^{obs})$

Multiple Imputation

- ▶ Rubin (1976), Schafer (1998), Van Buuren et al (1999), King et al (2000, 2015)
- ▶ **Idea:** Analysis should reflect uncertainty inherent in imputation.
- ▶ Complete data D (dimension $n \times p$), observed data D^{obs} , Missingness Matrix M
- ▶ **Assumption 1:** Missing at Random: $P(M|D) = P(M|D^{obs})$
- ▶ **Assumption 2:** Distributional $D \sim N_p(\mu, \Sigma)$.

Multiple Imputation

- ▶ Rubin (1976), Schafer (1998), Van Buuren et al (1999), King et al (2000, 2015)
- ▶ **Idea:** Analysis should reflect uncertainty inherent in imputation.
- ▶ Complete data D (dimension $n \times p$), observed data D^{obs} , Missingness Matrix M
- ▶ **Assumption 1:** Missing at Random: $P(M|D) = P(M|D^{obs})$
- ▶ **Assumption 2:** Distributional $D \sim N_p(\mu, \Sigma)$.
- ▶ 3 stage scheme

Multiple Imputation

- ▶ Rubin (1976), Schafer (1998), Van Buuren et al (1999), King et al (2000, 2015)
- ▶ **Idea**: Analysis should reflect uncertainty inherent in imputation.
- ▶ Complete data D (dimension $n \times p$), observed data D^{obs} , Missingness Matrix M
- ▶ **Assumption 1**: Missing at Random: $P(M|D) = P(M|D^{obs})$
- ▶ **Assumption 2**: Distributional $D \sim N_p(\mu, \Sigma)$.
- ▶ 3 stage scheme
 - ▶ **Imputation** : Expectation Maximization, Chained equations.

Multiple Imputation

- ▶ Rubin (1976), Schafer (1998), Van Buuren et al (1999), King et al (2000, 2015)
- ▶ **Idea**: Analysis should reflect uncertainty inherent in imputation.
- ▶ Complete data D (dimension $n \times p$), observed data D^{obs} , Missingness Matrix M
- ▶ **Assumption 1**: Missing at Random: $P(M|D) = P(M|D^{obs})$
- ▶ **Assumption 2**: Distributional $D \sim N_p(\mu, \Sigma)$.
- ▶ 3 stage scheme
 - ▶ **Imputation** : Expectation Maximization, Chained equations.
 - ▶ **Analysis**

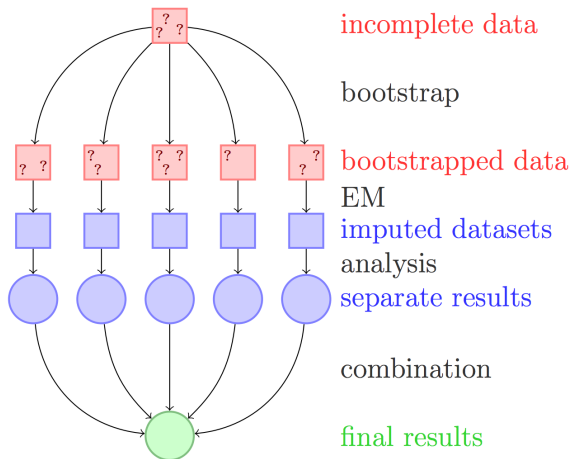
Multiple Imputation

- ▶ Rubin (1976), Schafer (1998), Van Buuren et al (1999), King et al (2000, 2015)
- ▶ **Idea**: Analysis should reflect uncertainty inherent in imputation.
- ▶ Complete data D (dimension $n \times p$), observed data D^{obs} , Missingness Matrix M
- ▶ **Assumption 1**: Missing at Random: $P(M|D) = P(M|D^{obs})$
- ▶ **Assumption 2**: Distributional $D \sim N_p(\mu, \Sigma)$.
- ▶ 3 stage scheme
 - ▶ **Imputation** : Expectation Maximization, Chained equations.
 - ▶ **Analysis**
 - ▶ **Combining Results**

Multiple Imputation

- ▶ Rubin (1976), Schafer (1998), Van Buuren et al (1999), King et al (2000, 2015)
- ▶ **Idea**: Analysis should reflect uncertainty inherent in imputation.
- ▶ Complete data D (dimension $n \times p$), observed data D^{obs} , Missingness Matrix M
- ▶ **Assumption 1**: Missing at Random: $P(M|D) = P(M|D^{obs})$
- ▶ **Assumption 2**: Distributional $D \sim N_p(\mu, \Sigma)$.
- ▶ 3 stage scheme
 - ▶ **Imputation** : Expectation Maximization, Chained equations.
 - ▶ **Analysis**
 - ▶ **Combining Results**
- ▶ 'R' Packages: Amelia, MICE, MI.

Multiple Imputation



Matrix Factorization: Generalized Low Rank Models

Matrix Factorization: Generalized Low Rank Models

- ▶ Low Rank and Low Norm approaches.

Matrix Factorization: Generalized Low Rank Models

- ▶ Low Rank and Low Norm approaches.
- ▶ Srebro (2004), Udell et al (2014).

Matrix Factorization: Generalized Low Rank Models

- ▶ Low Rank and Low Norm approaches.
- ▶ Srebro (2004), Udell et al (2014).
- ▶ Approximate matrix D (dimension $n \times p$) by $X'Y$.

Matrix Factorization: Generalized Low Rank Models

- ▶ Low Rank and Low Norm approaches.
- ▶ Srebro (2004), Udell et al (2014).
- ▶ Approximate matrix D (dimension $n \times p$) by $X'Y$.
- ▶ minimize $\sum_{i,j} L_{i,j}(x_i y_j, d_{ij}) + \gamma \sum_{i=1}^n r_i(x_i) + \gamma \sum_{j=1}^p r_j(y_j)$.

Matrix Factorization: Generalized Low Rank Models

- ▶ Low Rank and Low Norm approaches.
- ▶ Srebro (2004), Udell et al (2014).
- ▶ Approximate matrix D (dimension $n \times p$) by $X'Y$.
- ▶ minimize $\sum_{i,j} L_{i,j}(x_i y_j, d_{ij}) + \gamma \sum_{i=1}^n r_i(x_i) + \gamma \sum_{j=1}^p r_j(y_j)$.
 - ▶ L : Loss function (over columns) – quadratic, ordinal hinge, logistic, classification error etc.

Matrix Factorization: Generalized Low Rank Models

- ▶ Low Rank and Low Norm approaches.
- ▶ Srebro (2004), Udell et al (2014).
- ▶ Approximate matrix D (dimension $n \times p$) by $X'Y$.
- ▶ minimize $\sum_{i,j} L_{i,j}(x_i y_j, d_{ij}) + \gamma \sum_{i=1}^n r_i(x_i) + \gamma \sum_{j=1}^p r_j(y_j)$.
 - ▶ L : Loss function (over columns) – quadratic, ordinal hinge, logistic, classification error etc.
 - ▶ $r(\cdot)$: regularization functions – trace norm, max norm etc.

Matrix Factorization: Generalized Low Rank Models

- ▶ Low Rank and Low Norm approaches.
- ▶ Srebro (2004), Udell et al (2014).
- ▶ Approximate matrix D (dimension $n \times p$) by $X'Y$.
- ▶ minimize $\sum_{i,j} L_{i,j}(x_i y_j, d_{ij}) + \gamma \sum_{i=1}^n r_i(x_i) + \gamma \sum_{j=1}^p r_j(y_j)$.
 - ▶ L : Loss function (over columns) – quadratic, ordinal hinge, logistic, classification error etc.
 - ▶ $r(\cdot)$: regularization functions – trace norm, max norm etc.
 - ▶ X, Y : SVD good initialization.

Matrix Factorization: Generalized Low Rank Models

- ▶ Low Rank and Low Norm approaches.
- ▶ Srebro (2004), Udell et al (2014).
- ▶ Approximate matrix D (dimension $n \times p$) by $X'Y$.
- ▶ minimize $\sum_{i,j} L_{i,j}(x_i y_j, d_{ij}) + \gamma \sum_{i=1}^n r_i(x_i) + \gamma \sum_{j=1}^p r_j(y_j)$.
 - ▶ L : Loss function (over columns) – quadratic, ordinal hinge, logistic, classification error etc.
 - ▶ $r(\cdot)$: regularization functions – trace norm, max norm etc.
 - ▶ X, Y : SVD good initialization.
 - ▶ k, γ : chosen via crossvalidation.

Matrix Factorization: Generalized Low Rank Models

- ▶ Low Rank and Low Norm approaches.
- ▶ Srebro (2004), Udell et al (2014).
- ▶ Approximate matrix D (dimension $n \times p$) by $X'Y$.
- ▶ minimize $\sum_{i,j} L_{i,j}(x_i y_j, d_{ij}) + \gamma \sum_{i=1}^n r_i(x_i) + \gamma \sum_{j=1}^p r_j(y_j)$.
 - ▶ L : Loss function (over columns) – quadratic, ordinal hinge, logistic, classification error etc.
 - ▶ $r(\cdot)$: regularization functions – trace norm, max norm etc.
 - ▶ X, Y : SVD good initialization.
 - ▶ k, γ : chosen via crossvalidation.
- ▶ **Low Norm Models:** $r(x)$.

Matrix Factorization: Generalized Low Rank Models

- ▶ Low Rank and Low Norm approaches.
- ▶ Srebro (2004), Udell et al (2014).
- ▶ Approximate matrix D (dimension $n \times p$) by $X'Y$.
- ▶ minimize $\sum_{i,j} L_{i,j}(x_i y_j, d_{ij}) + \gamma \sum_{i=1}^n r_i(x_i) + \gamma \sum_{j=1}^p r_j(y_j)$.
 - ▶ L : Loss function (over columns) – quadratic, ordinal hinge, logistic, classification error etc.
 - ▶ $r(\cdot)$: regularization functions – trace norm, max norm etc.
 - ▶ X, Y : SVD good initialization.
 - ▶ k, γ : chosen via crossvalidation.
- ▶ **Low Norm Models:** $r(x)$.
- ▶ **Low Rank Models:** $\text{Rank}(X'Y) \leq k$.

Matrix Factorization: Generalized Low Rank Models

- ▶ Low Rank and Low Norm approaches.
- ▶ Srebro (2004), Udell et al (2014).
- ▶ Approximate matrix D (dimension $n \times p$) by $X'Y$.
- ▶ minimize $\sum_{i,j} L_{i,j}(x_i y_j, d_{ij}) + \gamma \sum_{i=1}^n r_i(x_i) + \gamma \sum_{j=1}^p r_j(y_j)$.
 - ▶ L : Loss function (over columns) – quadratic, ordinal hinge, logistic, classification error etc.
 - ▶ $r(\cdot)$: regularization functions – trace norm, max norm etc.
 - ▶ X, Y : SVD good initialization.
 - ▶ k, γ : chosen via crossvalidation.
- ▶ Low Norm Models: $r(x)$.
- ▶ Low Rank Models: $\text{Rank}(X'Y) \leq k$.
- ▶ Low Rank, Low Norm Models: Both

Matrix Factorization: Generalized Low Rank Models

- ▶ Low Rank and Low Norm approaches.
- ▶ Srebro (2004), Udell et al (2014).
- ▶ Approximate matrix D (dimension $n \times p$) by $X'Y$.
- ▶ minimize $\sum_{i,j} L_{i,j}(x_i y_j, d_{ij}) + \gamma \sum_{i=1}^n r_i(x_i) + \gamma \sum_{j=1}^p r_j(y_j)$.
 - ▶ L : Loss function (over columns) – quadratic, ordinal hinge, logistic, classification error etc.
 - ▶ $r(\cdot)$: regularization functions – trace norm, max norm etc.
 - ▶ X, Y : SVD good initialization.
 - ▶ k, γ : chosen via crossvalidation.
- ▶ Low Norm Models: $r(x)$.
- ▶ Low Rank Models: $\text{Rank}(X'Y) \leq k$.
- ▶ Low Rank, Low Norm Models: Both
- ▶ Julia Implementation: LowRankModels

Interpretations: Generalized Low rank Models

Interpretations: Generalized Low rank Models

- ▶ Low dimensional embedding

Interpretations: Generalized Low rank Models

- ▶ Low dimensional embedding
- ▶ Latent Variables

Interpretations: Generalized Low rank Models

- ▶ Low dimensional embedding
- ▶ Latent Variables
- ▶ Compression

Interpretations: Generalized Low rank Models

- ▶ Low dimensional embedding
- ▶ Latent Variables
- ▶ Compression
- ▶ Denoising

Interpretations: Generalized Low rank Models

- ▶ Low dimensional embedding
- ▶ Latent Variables
- ▶ Compression
- ▶ Denoising
- ▶ Probabilistic Interpretation

Interpretations: Generalized Low rank Models

- ▶ Low dimensional embedding
- ▶ Latent Variables
- ▶ Compression
- ▶ Denoising
- ▶ **Probabilistic Interpretation** \Leftarrow Equivalent to Multiple Imputation assumption when full rank.

Empirical Applications

- ▶ General Social Survey Data (GSS)
- ▶ National Longitudnal Survey of Youth (NLSY)
- ▶ Evaluation Strategy
- ▶ Caveats

Empirical Applications

- ▶ General Social Survey Data (GSS)
 - ▶ Sociological survey: adults in randomly selected US households.
- ▶ National Longitudinal Survey of Youth (NLSY)
- ▶ Evaluation Strategy
- ▶ Caveats

Empirical Applications

- ▶ General Social Survey Data (GSS)
 - ▶ Sociological survey: adults in randomly selected US households.
 - ▶ Data on attitudes and demographic characteristics.
- ▶ National Longitudinal Survey of Youth (NLSY)
- ▶ Evaluation Strategy
- ▶ Caveats

Empirical Applications

- ▶ **General Social Survey Data (GSS)**
 - ▶ Sociological survey: adults in randomly selected US households.
 - ▶ Data on attitudes and demographic characteristics.
- ▶ **National Longitudinal Survey of Youth (NLSY)**
 - ▶ Longitudinal dataset: Tracking cohort of young men and women over time.
- ▶ **Evaluation Strategy**
- ▶ **Caveats**

Empirical Applications

- ▶ **General Social Survey Data (GSS)**
 - ▶ Sociological survey: adults in randomly selected US households.
 - ▶ Data on attitudes and demographic characteristics.
- ▶ **National Longitudinal Survey of Youth (NLSY)**
 - ▶ Longitudinal dataset: Tracking cohort of young men and women over time.
 - ▶ Data on range of economic, psychological, demographic characteristics.
- ▶ **Evaluation Strategy**
- ▶ **Caveats**

Empirical Applications

- ▶ **General Social Survey Data (GSS)**
 - ▶ Sociological survey: adults in randomly selected US households.
 - ▶ Data on attitudes and demographic characteristics.
- ▶ **National Longitudinal Survey of Youth (NLSY)**
 - ▶ Longitudinal dataset: Tracking cohort of young men and women over time.
 - ▶ Data on range of economic, psychological, demographic characteristics.
- ▶ **Evaluation Strategy**
 - ▶ Subsets of the data used
- ▶ **Caveats**

Empirical Applications

- ▶ **General Social Survey Data (GSS)**
 - ▶ Sociological survey: adults in randomly selected US households.
 - ▶ Data on attitudes and demographic characteristics.
- ▶ **National Longitudinal Survey of Youth (NLSY)**
 - ▶ Longitudinal dataset: Tracking cohort of young men and women over time.
 - ▶ Data on range of economic, psychological, demographic characteristics.
- ▶ **Evaluation Strategy**
 - ▶ Subsets of the data used
 - ▶ 10% observed data held-out at random.
- ▶ **Caveats**

Empirical Applications

- ▶ **General Social Survey Data (GSS)**
 - ▶ Sociological survey: adults in randomly selected US households.
 - ▶ Data on attitudes and demographic characteristics.
- ▶ **National Longitudinal Survey of Youth (NLSY)**
 - ▶ Longitudinal dataset: Tracking cohort of young men and women over time.
 - ▶ Data on range of economic, psychological, demographic characteristics.
- ▶ **Evaluation Strategy**
 - ▶ Subsets of the data used
 - ▶ 10% observed data held-out at random.
 - ▶ Imputation models: Low Rank (Scaled), Low Rank (Unscaled), Trace Norm (Full Rank), Trace Norm (Low Rank), MICE
- ▶ **Caveats**

Empirical Applications

- ▶ **General Social Survey Data (GSS)**
 - ▶ Sociological survey: adults in randomly selected US households.
 - ▶ Data on attitudes and demographic characteristics.
- ▶ **National Longitudinal Survey of Youth (NLSY)**
 - ▶ Longitudinal dataset: Tracking cohort of young men and women over time.
 - ▶ Data on range of economic, psychological, demographic characteristics.
- ▶ **Evaluation Strategy**
 - ▶ Subsets of the data used
 - ▶ 10% observed data held-out at random.
 - ▶ Imputation models: Low Rank (Scaled), Low Rank (Unscaled), Trace Norm (Full Rank), Trace Norm (Low Rank), MICE
 - ▶ Loss calculated over hold out sample
- ▶ **Caveats**

Key Results: GSS

Key Results: GSS

- ▶ Overall Trace (Full Rank) had lowest loss, all Low Rank and Low Norm models outperformed MICE

Key Results: GSS

- ▶ Overall Trace (Full Rank) had lowest loss, all Low Rank and Low Norm models outperformed MICE
- ▶ Column-wise: $\approx 80\%$ columns had lower loss compared to MICE

Key Results: GSS

- ▶ Overall Trace (Full Rank) had lowest loss, all Low Rank and Low Norm models outperformed MICE
- ▶ Column-wise: $\approx 80\%$ columns had lower loss compared to MICE

▶ Summary Table

	LowRank (S)	LowRank (NS)	Trace (FR)	Trace (LR)	MICE
Loss/(10 ³)	18.50	15.80	14.40	15.80	20.60
%age reduction over MICE	10.10 %	23.40 %	30.10 %	23.00 %	–
%age cols w/ lower loss	73.50 %	84.60 %	87.20 %	84.60 %	–

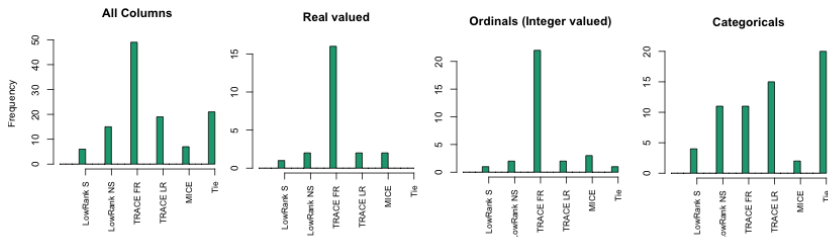
Key Results: GSS

- ▶ Overall Trace (Full Rank) had lowest loss, all Low Rank and Low Norm models outperformed MICE
- ▶ Column-wise: $\approx 80\%$ columns had lower loss compared to MICE

▶ Summary Table

	LowRank (S)	LowRank (NS)	Trace (FR)	Trace (LR)	MICE
Loss/(10^3)	18.50	15.80	14.40	15.80	20.60
%age reduction over MICE	10.10 %	23.40 %	30.10 %	23.00 %	—
%age cols w/ lower loss	73.50 %	84.60 %	87.20 %	84.60 %	—

▶ Method with lowest loss across columns



Key Results: NLSY

Key Results: NLSY

- ▶ Overall Trace (Full Rank) had lowest loss, all Low Rank and Low Norm models outperformed MICE

Key Results: NLSY

- ▶ Overall Trace (Full Rank) had lowest loss, all Low Rank and Low Norm models outperformed MICE
- ▶ Column-wise: $\approx 90\%$ columns had lower loss compared to MICE

Key Results: NLSY

- ▶ Overall Trace (Full Rank) had lowest loss, all Low Rank and Low Norm models outperformed MICE
- ▶ Column-wise: $\approx 90\%$ columns had lower loss compared to MICE

▶ Summary Table

	LowRank (S)	LowRank (NS)	Trace (FR)	Trace (LR)	MICE
Loss/(10 ³)	31.40	28.20	25.90	28.20	37.00
%age reduction over MICE	15.20 %	23.70 %	30.00 %	23.70 %	–
%age cols w/ lower loss	75.70%	92.90 %	94.30 %	94.30 %	–

Key Results: NLSY

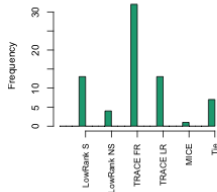
- ▶ Overall Trace (Full Rank) had lowest loss, all Low Rank and Low Norm models outperformed MICE
- ▶ Column-wise: $\approx 90\%$ columns had lower loss compared to MICE

▶ Summary Table

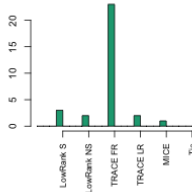
	LowRank (S)	LowRank (NS)	Trace (FR)	Trace (LR)	MICE
Loss/(10 ³)	31.40	28.20	25.90	28.20	37.00
%age reduction over MICE	15.20 %	23.70 %	30.00 %	23.70 %	—
%age cols w/ lower loss	75.70%	92.90 %	94.30 %	94.30 %	—

▶ Method with lowest loss across columns

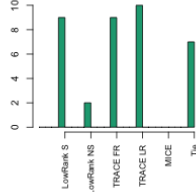
All Columns



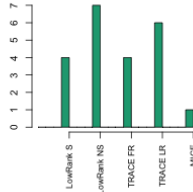
Integer Valued



Categoricals



Composition of Ties



Next Steps

- ▶ Probabilistic losses

Next Steps

- ▶ Probabilistic losses
- ▶ Max Norm regularizer

Next Steps

- ▶ Probabilistic losses
- ▶ Max Norm regularizer
- ▶ Replicating missingness patterns

Next Steps

- ▶ Probabilistic losses
- ▶ Max Norm regularizer
- ▶ Replicating missingness patterns
- ▶ Wrapper for Multiple Imputation

Next Steps

- ▶ Probabilistic losses
- ▶ Max Norm regularizer
- ▶ Replicating missingness patterns
- ▶ Wrapper for Multiple Imputation
- ▶ Extending GLRM to longitudinal data using Tensor Decomposition

Next Steps

- ▶ Probabilistic losses
- ▶ Max Norm regularizer
- ▶ Replicating missingness patterns
- ▶ Wrapper for Multiple Imputation
- ▶ **Extending GLRM to longitudinal data using Tensor Decomposition** \Leftarrow Future Work.

Thank you!
(Comments and Suggestions Welcome)