

Annotated bibliography

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1 Motivation: Challenges in historical record linkage

Record linkage in economics is most often studied by those who use historical U.S. data prior to the introduction of social security numbers (Abramitzky et al., 2019a; Aizer et al., 2016; Ferrie, 1996). These data tend to lack unique identifiers, so that individuals are primarily identified by their first and last name, and age¹, which are rarely unique within a given population. The non-uniqueness problem is exacerbated by typographical error, caused by low literacy rates and regional variations in names, as well as the record digitization process itself which introduces yet another possible source of error.

For example, Nix and Qian (2015) remark that an illiterate individual from Louisiana with the surname of Thibideaux, who chooses to move to another state, would likely have his name spelled phonetically as Tibido. Goeken et al. (2017) document that in two enumerations of St. Louis in the 1880 Census, nearly 46 percent of first names are not exact matches, and the Early Indicators project notes that 11.5 percent of individuals in the Oldest Old sample have a shorter first name in pension records than in the original Civil War enlistment

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¹Sometimes middle initial, birthplace, parent's name and birthplace, exact birthdate etc. are available; but data quality vary by application.

records (Costa et al. 2017).

Researchers use a variety of techniques – phonetic algorithms, string comparators, and probabilistic record linkage – to link records from different files despite errors that arise in the record generating process.

Compared to other fields where record linkage is a research goal in itself, record linkage in economics is seen as prerequisite to answering economic questions. Economists contribute to the record linkage literature by focusing on historic data; with care for the impact it has on subsequent inference.

This is problem bc Neter, Maynes, and Ramanathan (1965): small mismatch errors in finite population sampling can lead to a substantial bias in estimating the relationship between response errors and true values

Matching methods and estimation methods are studied separately, but really ought to be studied together.

2 Matching Methods

2.1 Survey Papers

Record linkage is such an intricate and frequent challenge that there are several books devoted to its study, and dozens of commercial and freely available software devoted to the task (Christen, 2012; Herzog et al., 2007). The research and open source systems include those developed by census bureaus, computer scientists, epidemiologists, statisticians, political scientists, and – only more recently – economists. A recent survey by Köpcke and Rahm (2010) evaluates eleven such systems.

The challenge in studying record linkage and its effects on inference, are magnified by

the fact that research on the topic occurs in disparate fields. Goldstein, Harron and Wade (2012) prove the same result that is published six years later in Hirukawa and Prokhorov (2018).

The father of modern record linkage, Winkler in Christen (2012) says: “Although individuals have introduced alternative classification methods based on Support Vector Machines, decision trees and other methods from machine learning, no method has consistently outperformed methods based on the Fellegi-Sunter model, particularly with large day-to-day applications with tens of millions of records”

Bailey et al. (2017) review literature on historical record linkage in US and examines performance of automated record linkage algorithms with two high-quality historical datasets and one synthetic ground truth. They conclude that no method consistently produces representative samples; machine linking has high number of false links and may introduce bias into analyses.

Abramitzky et al. (2018) have guide for researchers in the choice of which variables to use for linking, how to estimate probabilities, and then choose which records to use in the analysis. Created R code and stata command to implement the method

Abramitzky et al. (2019a) evaluate different automated methods for record linkage, specifically deterministic (like Ferrie and ABE papers), machine learning Feigenbaum approach, and the AMP approach with the EM algorithm. Document a frontier between type I and type II errors; cost of low false positive rates comes at cost of designating relatively fewer (true) matches. Humans typically match more at a cost of more false positives. They study how different linking methods affect inference – sensitivity of regression estimates to the choice of linking algorithm. They find that the parameter estimates are stable across linking methods. Find effect of matching algorithm on inference is small.

2.2 Surveys on Estimation Methods

“Evaluating bias due to data linkage error in electronic healthcare records” – compares the highest probability match (nearest neighbor) with prior-induced imputation

2.3 Matching Methods

Bailey et al. (2017) categorize historical linking algorithms (that match observations using name and age only) according to how they treat candidate pairs in the following four categories:

- M1: A perfect, unique match in terms of name and age similarity
- M2: A single, similar match that is slightly different in terms of age, name, or both
- M3: Many perfect matches, leading to problems with match disambiguation
- M4: Multiple similar matches that are slightly different in terms of age, name or both

Historical linking algorithms generally treat M1 cases as matches, but differ in how they treat M2, M3, and M4 candidate pairs. Generally, differences in M2 are solved deterministically by setting fixed-year band tolerances for matches, and probabilistically by estimating weights for the relative importance of age vs. name agreement. Multiple matches in M3/M4 are ignored, picked at random, given equal weights, or given weights proportional to the probability of being the true match. Table X below provides an overview of methods in literature based on these dimensions.

[Insert table here] Table includes

Talk also about how to evaluate these matching methods – what is desirable? How to estimate error rates ex post!

- Ferrie 1996, Abramitzky, BOustan and Eriksson (2012 2014 2017) Deterministic. Con-

servative methods require no other potential match with same name within a 5-year band , Nix and Qian

- Semi-automated Feigenbaum, Ruggles et al

3 Estimation Methods

3.1 Scheuren and Winkler (1993, 1997)

Scheuren and Winkler (1993) give a bias adjustment – use linkage probabilities to correct for failures in the matching step. However, Scheuren and Winkler (1997) (1997) is the first paper to propose a unified approach between the linkage and the analysis. But no theoretical results. lacks a convergence proof, etc.

3.2 Lahiri and Larsen (2005)

Lahiri and Larsen (2005) take as input two files are linked by a computerized record linkage technique (CRL). The true data pairs (x_i, y_i) are not observable; instead, the CRL produces pairs (x_i, z_i) in which z_i may or may not correspond to y_i . The (true) regression model is:

$$y_i = x_i' \beta + \epsilon_i, \quad E[\epsilon_i] = 0,$$

$$\text{var}(\epsilon_i) = \sigma^2, \quad \text{cov}(\epsilon_i \epsilon_j) = 0$$

but the researcher estimates this model with z_i as the dependent variable, where

$$z_i = \begin{cases} y_i & \text{with probability } q_{ii} \\ y_j & \text{with probability } q_{ij} \text{ for } j \neq i, j = 1, \dots, n \end{cases}$$

and $\sum_{j=1}^n q_{ij} = 1$, $i = 1, \dots, n$. Define $\mathbf{q}_i = (q_{i1}, \dots, q_{in})'$. The naive least squares estimator of β , which ignores mismatch errors, is given by:

$$\hat{\beta}_N = (\mathbf{X}'\mathbf{X})^{-1}\mathbf{X}'\mathbf{z}$$

An alternative to this naive estimator is one that minimizes the sum of absolute deviations, which decrease the influence of outliers and hence should decrease the impact of erroneously paired predictor and response values.

Note that $E(z_i) = \mathbf{w}_i'\beta$, with $\mathbf{w}_i = \mathbf{q}_i'\mathbf{X}_i = \sum_{j=1}^n q_{ij}x_j'$, and so the bias of $\hat{\beta}_N$ is given by

$$\text{bias}(\hat{\beta}_N) = [(X'X)^{-1}X'QX - I]\beta$$

Hence, if $Q = I$, then $\hat{\beta}_N$ is unbiased. This is equivalent to giving all potential matches the same weight (i.e. treating all matches as equally likely to be correct), as discussed in Anderson et al. (2019).

In order to reduce the bias of $\hat{\beta}_N$, Scheuren and Winkler (1993) observed that

$$\text{bias}(\hat{\beta}_N|y) = E[(\hat{\beta}_N - \beta)|y] = (X'X)^{-1}X'B,$$

where $B = (B_1, \dots, B_n)'$ and $B_i = (q_{ii} - 1)y_i + \sum_{j \neq i} q_{ij}y_j = \mathbf{q}_i'\mathbf{y} - y_i$, which is the difference between a weighted average of responses from all observations and the actual response y_i . Thus, if an estimator \hat{B} is available, the SW estimator is given by:

$$\hat{\beta}_{SW} = \hat{\beta}_N - (X'X)^{-1}X'\hat{B}$$

SW give a truncated estimator of B_i using the first and second highest elements of the vector q_i , $\hat{B}_i^{TR} = (q_{ij_1} - 1)z_{j_1} + q_{ij_2}z_{j_2}$, that can also be written more generally for an arbitrary number of elements of q_i . This means that $\hat{\beta}_{SW}$ is not unbiased, but, if the probability is

high that the best candidate link is the true link, then the truncation might produce a very small bias.

Using $E(z) = W\beta$, Lahiri and Larsen (2005) propose an exactly unbiased estimator of β :

$$\hat{\beta}_U = (W'W)^{-1}W'z$$

where $W = (w_1, \dots, w_N)'$, $w_i = q_i'X_i$ as above. They suggest using a truncated version of w_i , $w_i^{TR} = q_{ij_1}x_{j_1} + q_{ij_2}x_{j_2}$. Lahiri and Larsen (2005) use estimates of Q obtained from applying the Fellegi-Sunter/EM procedure, and observe that replacing Q with \hat{Q} yields unbiased estimates of β whenever \hat{Q} can be assumed to be independent of z . They argue that this is expected to be true in most applications, because the distribution of matching variables (e.g. first and last name, age), which determines the distribution of \hat{Q} , is usually independent of the response variable y (e.g. income), and hence of z .

Importantly, this assumption does not hold in some economics applications, such as the racial “passing” example from Nix and Qian (2015).

Lahiri and Larsen (2005) conclude that in simulations, least median regression is not sufficient to guard against matching errors, whereas the method of SW (1003) made a useful adjustment. Their method performed well across a range of situations, and the bootstrap procedure is useful for reflecting uncertainty due to matching.

3.3 Prior-Informed Imputation (Goldstein et al., 2012)

Goldstein et al. (2012), among others (Hirukawa and Prokhorov, 2018), show that choosing the match with the highest probabilistic weight leads to biased estimates. This bias increases as the threshold for acceptance increases, and when there is an association between the linkage error probabilities and the variables in the model of interest. An example of this is Lariscy (YEAR).

Prior-informed imputation (PII), proposed in Goldstein et al. (2012), aims to select the correct value for variables of interest, rather than accepting a single complete record as a link. Information from match probabilities in candidate linking records (the prior) is combined with information in unequivocally linked records.

An example of PII in practice is ?.

NOTABLY, uses 1-1 matching (no multiple matches). Also assume that the probability of matching on MV values is independent of the variable of interest. They recognize this is not often the case; i.e. different hospitals may have different distributions of the variable of interest, quality of recorded identifying info may also differ by center, creating lack of independence between probability of a match and variable of interest. This is shown to be a problem in ?

Use the usual FS/EM procedure to estimate probabilities of candidate pairs referring to a match. The result is each record i is associated with $\{y_{ij}\}$ and probabilities p_{ij} . Assume, wlog, that all variables follow a joint multivariate normal distribution² A lower threshold can be chosen so that records with probabilities less than a threshold are ignored. In practice, they recommend ignoring records that have no match on any matching variable; regard these records as having missing variables and use standard MI.

Denote distribution of variables in linking datafile A (y in ahl framework), conditional on variables in the file of interest B that they are linking to, by $f(Y^{A|B})$. Conditioning is on responses and any covariates in the imputation model, includes variables from A that are treated as auxiliary predictor variables in the imputation model. This conditional distribution is also multivariate normal.

For each record i , we compute a modified prior probability π_{ij} which is the likelihood

²If this is not the case for some of the observed variables, then a joint MVN distribution can be obtained using the latent MVN trick (for categorical variables, imputed values are back-transformed to their original scales).

component $f(Y^{A|B})$ multiplied by the prior p_{ij} , so that $\pi_{ij} \propto f(Y^{A|B})p_{ij}$. The normalized set π_i comprises the modified probability distribution for each i record in A.

Set a lower threshold for accepting a record as a true link, and if any records exceeds this, we choose that with the largest probability. If no record exceeds the threshold, then we regard the data values as missing and use standard multiple imputation. “The largest gain can be expected to arise when the probability of a link is associated with the values of the variables to be transferred. When the MAR assumption discussed earlier holds, then given a high enough threshold, the proposed procedure will produce unbiased estimates” Incorporating the likelihood component can be expected to lead more often to the correct record exceeding a given threshold.

Proposed method for FIXING THIS ASSUMPTION! Thus far assumed true matching record is located within the B file. But this may not be the case. Assume we have an estimate of mortality rate of individuals in A, π_d . If a proportion of the A file $\pi_m < \pi_d$ are unequivocally matched, then the probability that a randomly chosen remaining record in B is not a death from the A file is $\pi_r = 1 - (\pi_d - \pi_m)$. Therefore multiply p_i by $1 - \pi_r$ and add an extra pseudo-record with probability π_r with an associated code for a surviving patient.

3.4 Nix and Qian (2015)

This is a perfect application for estimating the mean using our methods! That is the goal of Nix and Qian (2015).

Nix and Qian (2015) study racial passing by linking individual U.S. census records to determine whether an individual’s recorded race changed from one census to the next. To achieve higher match rates than those of previous studies³, the authors develop methods for including individuals with multiple potential matches. These methods include selecting

³The authors match 61-67 percent of individuals. ABE (2012), Hornbeck and Naidu (2014), Long and Ferrie (2013), Mill and Stein (2012) have match rates around 30, 24, 22, 11-34 percent respectively

one match at random, and selecting the match that produces an upper/lower bound for estimating the “passing” rate.

Nix and Qian (2015) also use the unmatched individuals from their data to calculate absolute bounds for the population passing rates. For a given algorithm, the absolute upper bound is obtained by using the “upper bound” configuration of data, combined with assuming that all unmatched individuals passed. The lower bound is obtained in the same way, assuming that none of the excluded individuals passed.

Nix and Qian (2015) argue that increasing the match rate improves the bounds around any true population statistic, even though their methods introduce random measurement error in the estimand. Below is a visual of their complex blocking strategy.

Figure 1: Nix and Qian (2015) blocking strategy

Figure A.8: Average Number of Potential Matches



3.5 Bleakley and Ferrie (2016)

Bleakley and Ferrie (2016) assign equal probability of winning (matched variable equal to $1/n$) to all n individuals matched to the same winner. The goal is to estimate the treatment effect of winning a parcel in the lottery by comparing mean outcomes for winners and losers in a simple bivariate regression with a dummy variable for winning a parcel on the right-hand side. Here, winning the lottery is coded as 0 or $1/n$, where n is the number of matches for person i . [Think about how this compares to ahl method]

3.6 Other ideas to include?

Hirukawa and Prokhorov (2018) give OLS methods for nearest neighbor matched samples. Not explicitly the probabilistic record linkage framework, although the authors use this term. Could apply their methods for an appropriately defined metric for matching variables (i.e. Jaro-Winkler string distance), and use a nearest neighbor matching rule to assign 1-1 matches (although some y may get mapped to multiple x).

Enamorado procedures Survey paper from handbook of econometrics

”However, the analytic estimates of precision in Lahiri and Larsen (2005) are poor for 1-1 probabilistic linkage (Chipperfield and Chambers 2015)” As a quality measure, Christen (2012) suggests precision, which is the proportion of links that are true matches. Winglee et al. (2005) use a simulation-based approach, Simrate to estimate linkage quality. Their method uses the observed distribution of data in matched and non-matched pairs to generate a large simulated set of record

FROM <https://arxiv.org/pdf/1901.04779.pdf>

Simulation Idea

Could use only simulation data, with variety of possible biases, motivated by the applications above. For example, motivated by N-Q, introduce error with geographical relocation. Then test which techniques are robust to these types of sample selection/error.

I will compare estimates of Type I/ Type II error to ACTUAL Type I/ Type II error rates, and say that authors need to estimate their errors!! Not just report the match rate. Use estimates from Chipperfield (2018) maybe <https://onlinelibrary.wiley.com/doi/epdf/10.1111/insr.12246>

4 Bird’s eye view of literature

Record linkage surveys

- Books on record linkage: Christen (2012); Herzog et al. (2007)
- Review of free software tools: Köpcke and Rahm (2010)
- Survey of RL techniques in economics : Bailey et al. (2017), Abramitzky et al. (2019a)
- Surveys by the “father” and “mother” of modern record linkage (Winkler, 1999; Harron et al., 2012)
- Comparison of deterministic vs. probabilistic matching methods (Doidge and Harron, 2018)

Matching methods

- Probabilistic Record Linkage (Fellegi and Sunter, 1969; Abramitzky et al., 2018)
- Prior-informed imputation (Goldstein et al., 2012)
- Bayesian “Beta” Record Linkage (Sadinle, 2017)
- Deterministic methods for economics (Ferrie, 1996; Abramitzky et al., 2012, 2019b)
- Deterministic methods for bounding parameter (Nix and Qian, 2015)
- Allow multiple matches by imputing equal weight values (Bleakley and Ferrie, 2016)

Estimation methods

- Integrated matching and estimation procedures
 - Iterative matching, regression analysis, imputation (Scheuren and Winkler, 1997)
 - Bayesian matching and population size (Tancredi and Liseo, 2015)
- Bias corrections for regression with matched data
 - Bias correction for regression (Scheuren and Winkler, 1993; Lahiri and Larsen, 2005)
 - Weighted least squares-based bias correction for linear and logistic regression (Hof and Zwinderman, 2012)
 - Bias correction for NN-matching (Hirukawa and Prokhorov, 2018)
- GMM with multiple matches (Anderson et al., 2019)

References

- R. Abramitzky, L. Boustan, K. Eriksson, J. Feigenbaum, and S. Perez, “Automated linking of historical data,” *NBER Working Paper*, 2019.
- A. Aizer, S. Eli, J. Ferrie, and A. Lleras-Muney, “The long-run impact of cash transfers to poor families,” *American Economic Review*, vol. 106, no. 4, pp. 935–71, April 2016. [Online]. Available: <http://www.aeaweb.org/articles?id=10.1257/aer.20140529>
- J. P. Ferrie, “A new sample of males linked from the public use microdata sample of the 1850 u.s. federal census of population to the 1860 u.s. federal census manuscript schedules,” *Historical Methods*, vol. 29, no. 4, pp. 141–156, 1 1996.
- E. Nix and N. Qian, “The fluidity of race: “Passing” in the united states, 1880-1940,” National Bureau of Economic Research, Working Paper 20828, January 2015. [Online]. Available: <http://www.nber.org/papers/w20828>
- P. Christen, *Data Matching: Concepts and Techniques for Record Linkage, Entity Resolution, and Duplicate Detection*. Springer Publishing Company, Incorporated, 2012.
- T. N. Herzog, F. J. Scheuren, and W. E. Winkler, *Data Quality and Record Linkage Techniques*, 1st ed. Springer Publishing Company, Incorporated, 2007.
- H. Köpcke and E. Rahm, “Frameworks for entity matching: A comparison,” *Data Knowledge Engineering*, vol. 69, pp. 197–210, 02 2010.
- M. Hirukawa and A. Prokhorov, “Consistent estimation of linear regression models using matched data,” *Journal of Econometrics*, vol. 203, no. 2, pp. 344 – 358, 2018. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S0304407617302464>
- M. Bailey, C. Cole, M. Henderson, and C. Massey, “How well do automated linking methods perform? lessons from u.s. historical data,” National Bureau of Economic Research, Working Paper 24019, November 2017. [Online]. Available: <http://www.nber.org/papers/w24019>
- R. Abramitzky, R. Mill, and S. Perez, “Linking individuals across historical sources: a fully automated approach,” National Bureau of Economic Research, Working Paper 24324, February 2018. [Online]. Available: <http://www.nber.org/papers/w24324>
- F. Scheuren and W. Winkler, “Regression analysis of data files that are computer matched,” *Survey Methodology*, vol. 19, 01 1993.
- , “Regression analysis of data files that are computer matched - part ii,” *Survey Methodology*, vol. 23, 01 1997.
- P. Lahiri and M. D. Larsen, “Regression analysis with linked data,” *Journal of the American Statistical Association*, vol. 100, no. 469, pp. 222–230, 2005. [Online]. Available: <http://www.jstor.org/stable/27590532>

- R. Anderson, B. Honore, and A. Lleras-Muney, “Estimation and inference using imperfectly matched data,” *Working paper*, August 2019. [Online]. Available: <http://www.github.com/rachelsanderson/ImperfectMatching>
- H. Goldstein, K. L. Harron, and A. M. Wade, “The analysis of record-linked data using multiple imputation with data value priors.” *Statistics in medicine*, vol. 31 28, pp. 3481–93, 2012.
- H. Bleakley and J. Ferrie, “Shocking behavior: Random wealth in antebellum georgia and human capital across generations,” *The Quarterly Journal of Economics*, vol. 131, no. 3, pp. 1455–1495, 2016. [Online]. Available: <https://doi.org/10.1093/qje/qjw014>
- W. Winkler, “The state of record linkage and current research problems,” *Statist. Med.*, vol. 14, 10 1999.
- K. Harron, A. Wade, B. Muller-Pebody, H. Goldstein, and R. Gilbert, “Opening the black box of record linkage,” *Journal of Epidemiology & Community Health*, vol. 66, no. 12, pp. 1198–1198, 2012. [Online]. Available: <https://jech.bmj.com/content/66/12/1198.2>
- J. Doidge and K. Harron, “Demystifying probabilistic linkage,” *International Journal for Population Data Science*, vol. 3, 01 2018.
- I. P. Fellegi and A. B. Sunter, “A theory for record linkage,” *Journal of the American Statistical Association*, vol. 64, pp. 1183–1210, 1969.
- M. Sadinle, “Bayesian estimation of bipartite matchings for record linkage,” *Journal of the American Statistical Association*, vol. 112, no. 518, p. 600?612, 2017.
- R. Abramitzky, L. P. Boustan, and K. Eriksson, “Europe’s tired, poor, huddled masses: Self-selection and economic outcomes in the age of mass migration,” *American Economic Review*, vol. 102, no. 5, pp. 1832–56, May 2012. [Online]. Available: <http://www.aeaweb.org/articles?id=10.1257/aer.102.5.1832>
- , “To the new world and back again: Return migrants in the age of mass migration,” *ILR Review*, vol. 72, no. 2, pp. 300–322, 2019. [Online]. Available: <https://doi.org/10.1177/0019793917726981>
- A. Tancredi and B. Liseo, “Regression analysis with linked data: problems and possible solutions,” *Statistica*, vol. 75, no. 1, pp. 19–35, 2015. [Online]. Available: <https://rivista-statistica.unibo.it/article/view/5821>
- M. H. P. Hof and A. H. Zwinderman, “Methods for analyzing data from probabilistic linkage strategies based on partially identifying variables,” *Statistics in Medicine*, vol. 31, no. 30, pp. 4231–4242, 2012. [Online]. Available: <https://onlinelibrary.wiley.com/doi/abs/10.1002/sim.5498>