Variety and Mainstays of the R Developer Community

by Lijin Zhang, Xueyang Li, and Zhiyong Zhang

Abstract The thriving developer community has a significant impact on the widespread use of R software. To better understand this community, we conducted a study analyzing all R packages available on CRAN. We identified the most popular topics of R packages by text mining the package descriptions. Additionally, using network centrality measures, we discovered the important packages in the package dependency network and influential developers in the global R community. Our analysis showed that among the 20 topics identified in the topic model, *Data Import, Export, and Wrangling*, as well as *Data Visualization, Result Presentation, and Interactive Web Applications*, were particularly popular among influential packages and developers. These findings provide valuable insights into the R community.

1 Introduction

Initially started as a personal project by Ross Ihaka and Robert Gentleman (Ihaka and Gentleman, 1996), R has evolved into one of the most widely used and powerful software packages in the field of data science. It is used across a wide range of academic fields and industries. For example, Lai et al. (2019) showed that 58% of the papers from 30 ecology journals in 2017 reported using R for data analysis. Another example is Bioconductor (Gentleman et al., 2004), a popular R software repository for computational biology and bioinformatics, which has over 2,000 R packages for genetic data analysis. Moreover, **ggplot2** (Wickham, 2011), a well-known R package for data visualization, has been cited more than 30,000 times. Courses teaching R are also in high demand in data science programs (Zhang and Zhang, 2021). Fox and Leanage (2016) analyzed the papers published in the Journal of Statistical Software (JSS) between 1996 and 2016, and found that 75% of the articles were about R, which demonstrated the dominance of R software projects in JSS.

The R developer community plays an important role in maintaining a healthy ecosystem of R packages and increasing R's popularity (Chambers, 2020; Tippmann, 2015). The R ecosystem comprises of the base packages developed by the R Core team and user-contributed packages (German et al., 2013). The Comprehensive R Archive Network (CRAN) is a well-known package repository. Fox (2009) suggested that the CRAN package archive is probably the most important driving force for the growing usage of R. The package system provides essential tools for users to develop packages and promotes the sharing of newly-developed methods and ideas throughout the community. Fox (2009) found that the growth of CRAN packages from 2000 to 2009 was approximately exponential. Since then, the number of new CRAN packages has slowed down a bit, but has otherwise maintained a steady pace (Fox and Leanage, 2016). As of 27th November 2022, there are 18898 packages available on CRAN, more than eight times of the number in 2009.

As the number of CRAN packages increases, the flat organization of these packages (Fox and Leanage, 2016) makes it difficult for user to identify popular and important packages on CRAN. Silge et al. (2018) suggested that the huge size of the CRAN package archive has already made it difficult for users to understand the merits of packages and the relationships among packages. Although some resources such as CRAN Task Views (Zeileis, 2005) group packages related to specific topics, they cannot cover the enormous number of CRAN packages or give an overall view of the various topics covered by the CRAN packages. Moreover, as the number of CRAN packages increases, the newly-developed packages are often built upon other user-contributed packages. It is, therefore, essential to explore the package dependency network and identify the influential developers who lead the R ecosystem.

As such, this study aims to conduct a broad survey of the R developer community. Specifically, the goal of this paper is two-fold: 1) to investigate the popular topics of the R ecosystem, and 2) to explore the influential packages and authors in the R developer community.

The large amount of information on CRAN is a challenge but also a great resource for understanding the R community. To investigate this community, this paper uses text mining and network analysis techniques, with a focus on analyzing package descriptions and the relationships between packages and authors. The paper is structured as follows. First, we analyze the textual data of CRAN package descriptions to identify the various topics of the R ecosystem. Second, a package dependency network, an author collaboration network, and a bipartite network of packages and authors are built to determine which packages and authors play important roles based on the network statistics for the development of the R ecosystem. Finally, we present a detailed discussion of our findings.

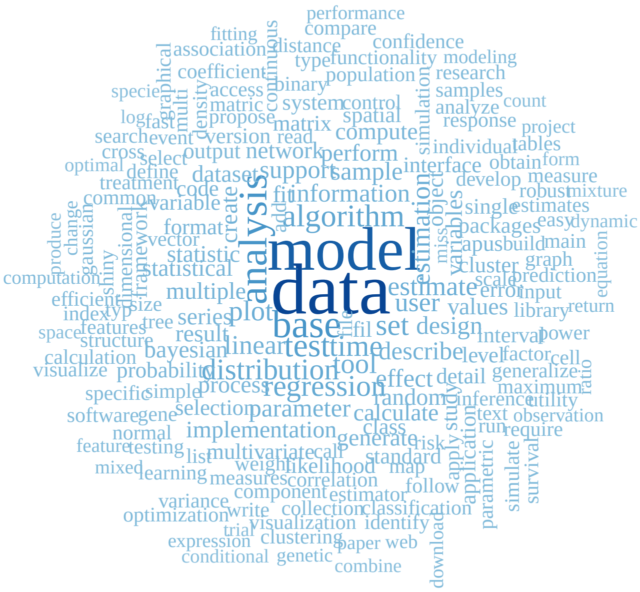


Figure 1: Word cloud of the top 200 frequently used words in the CRAN package descriptions.

2 Identifying the Main Topics of the R Packages

Our first goal is to understand what kind of topics and methods are currently covered in the packages of R. For this purpose, we extracted the descriptions of all 18898 packages from CRAN on 27th November 2022. The mean of the length of package descriptions is 60.15 words, ranging from 1 to 1207 words. Note that data and code of this paper are available at `https://github.com/zhanglj37/R_Developer_Community`, with which the results in this article can be replicated. Through text analysis technique, we explored the frequently used words and phrases to investigate the focuses of R developers, and conducted topic modeling to identify the main topics of the R ecosystem.

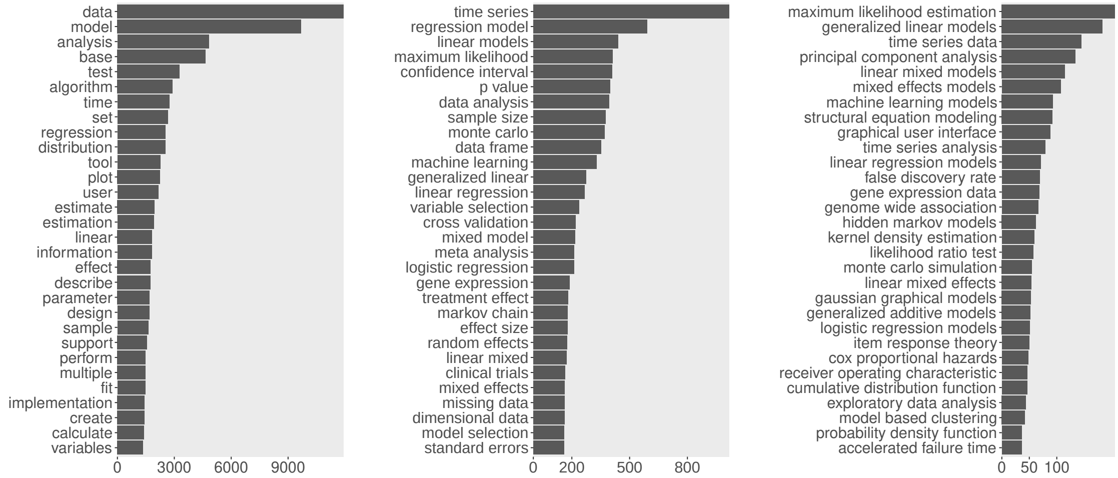
2.1 Data Cleaning

The pre-processing of the package descriptions includes five steps: 1) we converted the upper case letters to lower cases, 2) we deleted the web links, DOI (Digital Object Identifier) links of publications, and numbers (e.g., *1993*), and 3) we removed the common stopwords (e.g., *the, a*) and some commonly-used words with limited meaning (e.g., *package, provide, method*). Moreover, to unify different forms of the same root-words, we further 4) singularized plural nouns using the **SemNetCleaner** package (Christensen and Kenett, 2019), and 5) lemmatized verbs using the **spacyr** package (Benoit and Matsuo, 2020).

2.2 Word and Phrase Frequency

In Figure 1, a word cloud depicts the top 200 frequently used words in the package descriptions. Each of these 200 words was used more than 400 times. Four of them appeared more than 4,000 times (*data, model, analysis, base*), and *data* is the only one appeared more than 10,000 times. These words (e.g., *data, model*) are related to data analysis and were also commonly used in data science curricula (Zhang and Zhang, 2021).

Figure 2 includes the top 30 frequently used one-, two-, and three-word phrases in the package descriptions, including phrases that are related to statistical models (e.g., *regression model, structural equation modeling*), estimation methods (e.g., *least squares, maximum likelihood estimation*), different types of datasets (e.g., *high dimensional data, gene expression data*), and other common and general terms in data science (e.g., *data analysis, variable selection, open source*). We also explored the frequently used four-word phrases, and the top phrases include *Markov chain Monte Carlo* (141 times), *genome wide*



(a) Word (b) Two-word phrases (c) Three-word phrases

Figure 2: Top 30 frequently used words and phrases in the CRAN package descriptions.

association study (51 times), *single cell RNA sequencing* (43 times), *generalized linear mixed model* (36 times), *cox proportional hazards model* (30 times), and *random effects meta analysis* (15 times). Moreover, we found two informative six-word phrases that represent the journals that were commonly mentioned in the package descriptions: *Journal of the American Statistical Association* (22 times) and *Journal of Computational and Graphical Statistics* (12 times).

2.3 Topic Modeling

To identify relevant thematic features of the CRAN R packages, we conducted topic modeling based on the package descriptions using the **topicmodels** (Grün and Hornik, 2011) package. We used the Latent Dirichlet allocation (LDA; Blei et al., 2003) method to reveal the latent structures in R package descriptions. LDA assumes that each document (i.e., the description document of each package) is a mixture of topics, and each topic consists of a mixture of words (Silge and Robinson, 2017).

To fit the model, we first determined the number of topics. For each specified number of topics, ranging from 2 to 30, we built the LDA models with 100 different random number seeds to improve the robustness of results. In each replication, the 5-fold cross-validation technique was employed. We assessed the performance of the LDA models by calculating their perplexity under different numbers of topics. A low perplexity score indicates better model performance (Bao and Datta, 2014). Results suggest that the best fit to the data was a model with 19 topics, followed by the 21- and 20-topic models (Figure 3). In the 100 replications of analysis, the 19-topic model was selected as the best model most frequently, followed by the 21-, 20-, 18-, and 17-topic models. By exploring the meaning of each topic in each model, we found that the model with 20 topics offered the best interpretability. The 21-topic model identified three topics which are hard to distinguish because they were all about mixed models, Bayesian analysis, linear regression, and psychometrics. Compared to the 19-topic model, the 20-topic model was easier to interpret because it clearly separated the topics of *Generalized Linear Modeling and Mixed Models*, and *Psychometrics*. We also examined the inflection points in the performance curve (Figure 3). We found that the 9-topic and 10-topic models could not clearly differentiate many topics, resulting in many similar topics with overlapping components. Therefore, we finally adopted the 20-topic model.

The R package **ctv** (CRAN Task Views) introduces the relevant packages of 42 topics (e.g., Bayesian Inference, Chemometrics, Econometrics). We further compared the identified 20 topics with the topics classified in the CRAN Task Views and highlighted their connections in Table 1. In detail, the main topics recovered from the 20-topic LDA model, in no particular order, were listed below.

1. Supporting Packages Keywords of this topic include *data, book, support, ISBN(International Standard Book Number), tool*, and *publication*. This topic pertains to packages that offer supporting functions for other packages (e.g., **iemisc**) and/or provide supplementary materials (e.g., datasets) for books, courses, and other packages (e.g., **EnvStats**, **AER**, **uwo4419**, **ACSWR**, **mosaic**).

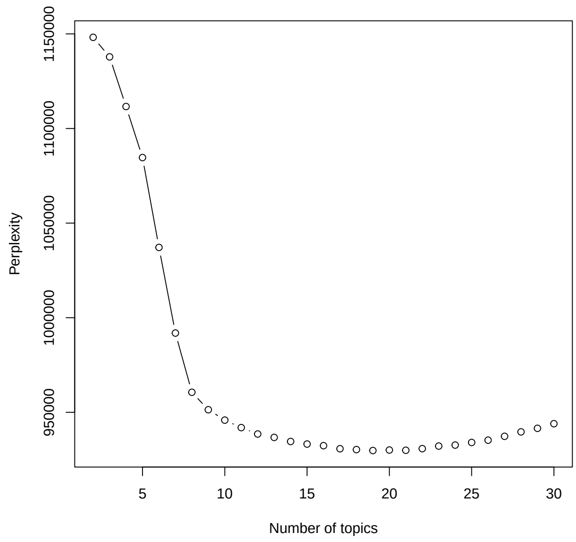


Figure 3: Mean perplexities of topic models with different number of topics.

2. Causal Inference This topic deals with causal inference, and its keywords include *effect, treatment, causal, outcome, propensity*, and *intervention*. Packages of this topic are related to the CRAN Task View of Causal Inference. Example packages are **CBPS** which contains methods for moments-based propensity score estimation, **BCEE** for Bayesian Causal Effect Estimation, and **CausalGAM** for estimation of causal effects with generalized additive models.

3. Numerical Mathematics Keywords of this topic include *matrix, sparse, covariance, correlation, vector, row, column*, and *decomposition*. It is related to a CRAN Task View of Numerical Mathematics. Packages identified by this topic include **Matrix**, a core package for sparse and dense matrix classes and methods, **PRIMME**, an R interface to a C library for computing eigenvalues, **SparseM**, a package with sparse linear algebra functions.

4. Classification This topic is about classification and includes keywords such as *variable, split, random, forest, tree, category*, and *feature*. Example packages include **randomForest** for classification based on a forest of trees, **tree** containing functions for classification and regression trees, **rpart** for recursive partitioning and regression trees, and **C50** for fitting C5.0 classification trees and rule-based models. Some of the packages identified by this topic can be found in the CRAN Task View of Machine Learning and Statistical Learning.

5. Regression Analysis and Regularization This topic is about regression analysis and regularization, with words such as *linear, regression, model, L1, lasso, ridge, shrinkage, procedure*, and *regularization* appearing with high probability. It is related to the packages for regularization methods and regression models (e.g., **glmnet** for lasso and elastic-net regularized generalized linear models (GLMs), **penalized** for applying ridge and lasso regularization in GLMs and Cox proportional hazards models, and **bravo** for Bayesian variable selection with ultra-high dimensional linear regression models.).

6. Genetics Keywords of this topic include terms related to genetics, such as *gene, RNA (Ribonucleic Acid), DNA (DeoxyriboNucleic Acid), sequence, cell*, and *phenotype*. This topic identifies the packages for analyzing biological data, especially genetic data (e.g., **jetset**, **Seurat**, **scBio**).

7. Datasets High probability words of this topic include *data, survey, questionnaire, sample, collection, census*, and *report*. This topic is mainly about a special kind of packages for providing datasets (especially survey data) instead of functions for statistical methods. For example, **spiR** is for social progress index data, **PakPMICS2018** is for survey data of a specific project conducted from 2017 to 2018, **USpopcenters** is about united stats centers of population data.

Table 1: Relevant CRAN Task Views of each topic identified in the topic model.

Topic	CRAN Task Views
1. Supporting Packages	Teaching Statistics
2. Causal Inference	Causal Inference
3. Numerical Mathematics	Numerical Mathematics
4. Classification	Machine Learning & Statistical Learning
5. Regression Analysis and Regularization	Machine Learning & Statistical Learning
6. Genetics	Statistical Genetics
7. Datasets	Databases with R
8. Cluster Analysis and Network Analysis	Cluster Analysis & Finite Mixture Models, gRaphical Models in R
9. Machine Learning	Machine Learning & Statistical Learning
10. NHST and Multiple Comparison	-
11. Probability Distributions and Bayesian Analysis	Probability Distributions, Bayesian Inference
12. Color Patterns and R Objects	-
13. Phylogenetics	Phylogenetics
14. Time Series Analysis	Time Series Analysis
15. Data Import, Export, and Wrangling	-
16. Computational Efficiency	Optimization and Mathematical Programming, High-Performance and Parallel Computing with R
17. Experimental Design and Clinical Trails	Clinical Trial Design, Monitoring, and Analysis, Design of Experiments & Analysis of Experimental Data
18. Data Visualization, Result Presentation, and Interactive Web Applications	Graphic Displays & Dynamic Graphics & Graphic Devices & Visualization, Reproducible Research Web Technologies and Services
19. Generalized Linear Modeling and Mixed Models	Mixed, Multilevel, and Hierarchical Models in R
20. Psychometrics	Psychometric Models and Methods

Note. NHST = Null Hypothesis Significance Testing.

8. Cluster Analysis and Network Analysis Keywords of this topic are related to two sub-topics. First, *network, gaussian, graphical, node, edge*, and *igraph* are commonly used in network analysis. Example packages include **igraph** and **sna**. Second, *cluster, class, kernel* are relevant to Cluster Analysis. Example packages include **cluster**, **kml** for implementing k-means clustering on longitudinal data, **flexclust** for providing flexible cluster algorithms. Cluster analysis and network analysis were identified in one topic perhaps because there are some packages for clustering based on correlation matrices and network modeling (e.g., **DirectedClustering**, **linkcomm**, **clusterGeneration**).

9. Machine Learning With keywords such as *algorithm, machine, learning, training*, and *prediction*, this topic is mainly about machine learning. The CRAN Task View of Machine Learning and Statistical Learning lists and classifies the packages of this topic, for example, packages for neural networks, deep learning (e.g., **RcppDL**, **deepnet**). Some packages are related to both this topic and the topic of regularization (e.g., **bmrm**). Courses of this topic are also very common in data science programs, including *Neural Networks and Deep Learning*, and *Machine Learning and Big Data* (Zhang and Zhang, 2021).

10. Null Hypothesis Significance Testing (NHST) and Multiple Comparison This topic encompasses NHST and Multiple Comparison, and its keywords include *test, hypothesis, null, multiple, comparison*, and *significance*. Relevant packages include **onewaytests** for NHST, **PMCMRplus** and **conover.test** for multiple comparisons among multiple groups.

11. Probability Distributions and Bayesian Analysis This topic centers around the word *distribution* and includes other relevant terms such as *probability, binomial, poisson, density, Bayesian, MCMC (Markov chain Monte Carlo), chain, prior, posterior*, and *sampler*. Probability and Bayesian analysis were identified in one topic because they share the main keyword *distribution* (i.e., probability distribution, prior distribution, and posterior distribution). Example packages include **extraDistr** for various univariate and multivariate distributions, **gnorm** for generalized normal or exponential power distributions, **bayesmix** for Bayesian mixture models, and **mcmc**. The CRAN Task Views of Probability Distributions and Bayesian provided a detailed summary of packages related to this topic.

12. Color Patterns and R Objects Keyword of this topic include *class, object, s4*, and*r6* which are related to R objects, and *color, png, image*, and *palettes* which are about visualization. For the R objects, example packages are **R6**, **R62S3**, and **fastdigest**. For the visualization, most packages identified by this topic are designed to provide color patters for plotting (e.g., **colormap**, **ggpattern**). Package

ggplot2 is also identified by this topic, but its relationship with the topic 18 (Data Visualization, Result Presentation, and Interactive Web Applications) is higher than its relationship with this topic.

13. Phylogenetics This topic is mainly about phylogenetics, with high probability words including *phylogenetic, specie, signal, taxonomic, animal, pedigree*, and *biodiversity*. Packages related to this topic include **phytools** which provides functions for phylogenetic analysis, **geiger** for fitting macroevolutionary models to phylogenetic trees, and **phylosignal** for exploring the phylogenetic signal. The CRAN Task View Phylogenetics also summarized packages related to this topic.

14. Time Series Analysis This topic is mainly about time series analysis. The high probability words associated with this topic include *time, series, change, dynamic, forecast, growth, trend*, and *lag*. There is a CRAN Task View of this topic that introduces many packages for handling time series data, for example, **tseries** for time series analysis, and **forecast** that provides forecasting functions for time series models.

15. Data Import, Export, and Wrangling This topic includes keywords such as *read, load, import, write, convert*, and *create*, which are commonly-used verbs for naming R functions for data import, export and wrangling. Example packages include **asciiSetupReader**, which can read fixed-width ASCII data files, **adfExplorer**, which can import and export Amiga disk files, and **dplyr**, "a grammar of data manipulation."

16. Computational Efficiency This topic is related to computational efficiency, with keywords including *run, C++, fast, efficient, Rcpp, efficient*, and *parallel*. Many packages associated with this topic call compiled C++ code from R to improve performance (e.g., **Rcpp**), and provide utilities for parallel computation (e.g., **future.callr**, **foreach**, **doParallel**).

17. Experimental Design and Clinical Trails This topic focuses on the design and data analysis of experiments and clinical trials. High probability words include *design, treatment, control, trial, clinical, sample, size, endpoint, stage, dose*, and *experimental*. The CRAN Task Views of Clinical Trial Design and Experimental Design summarize two lists of R packages concerning this topic. Here we listed some example packages such as **TrialSize** for sample size determination in clinical research, and **visit** for phase I dose-escalation study design.

18. Data Visualization, Result Presentation, and Interactive Web Applications Packages and keywords of this topic can be classified into three sub-topics. First, keywords such as *ggplot2, color, graph, image*, and *plot* are related to data visualization. Example packages include **ggplot2** and **lattice**. The second sub-topic is about presenting results, with keywords such as *table, chart*, and *figure*. Other keywords include *format, html, document, markdown, rmarkdown*, and *latex* which are mainly about R markdown tools for generating dynamic reports. Example packages are R markdown-related tools including **knitr** and **bookdown**, and formatting tools such as **styler** and **pander**. The third sub-topic relates to using R to build interactive web applications. Words relevant to this sub-topic include *shiny, widget, web*, and *XML*, and example packages include **shiny** and **webshot**.

In addition, there are many packages related to more than one sub-topic. For example, **ANOVAShiny** was built based on **rmarkdown** and **shiny**, and **Factoshiny** was developed with **shiny** and **ggplot2** for conducting factorial analysis and drawing graphs with a shiny application. There are also corresponding lists of this topic on CRAN Task Views, and courses in data science programs (e.g., *Data Visualization*, *Data Presentation and Visualization with R*; Zhang and Zhang, 2021).

19. Generalized Linear Models and Mixed Models This topic is related to generalized linear modeling, with keywords such as *model, regression, linear, fit, mixed, logistic*, and *GLM (Generalized Linear Modeling)*. Packages associated with this topic include **dglm** for building double generalized linear models, **brms** for Bayesian Regression Models, **nlme** for linear mixed models (LMMs), and **mbest** for large nested LMMs.

20. Psychometrics The high probability words related to this topic include *factor, item, response, latent, IRT (Item Response Theory)*, and *choice*. There is a detailed list on the CRAN Task Views about this topic. Here we listed some example packages: **mirt** for multidimensional item response theory, **difR** for detecting differential item functioning, and **CDM** for cognitive diagnosis models.

3 Identifying Key Packages and Key Package Developers

To investigate the key packages contributing to the R ecosystem and the notable authors who significantly support the R community, we conducted network analysis. We extracted package dependency and authorship information from CRAN and used **cranly** (Kosmidis, 2019) and **igraph** (Csárdi et al., 2006) to build three networks: 1) a package dependency network, 2) an author collaboration network, and 3) a bipartite network of packages and authors. Influential nodes were identified in these three networks. We first introduce the one-mode network (i.e., network with one type of node) of packages and authors below.

The R package dependency network was built based on the CRAN R packages and their dependent packages, including the base and recommended R packages that are included in the default installation of R. It is a directed and weighted network, and a sub-graph is presented in Figure 4(a). Specifically, the arrow from package A to package B indicates that A depends on, imports, suggests, link to, or is enhanced by B. Table 2 presents the detailed definitions and frequencies of these relationships (R Core Team, 2021). We assigned the weights of edges as $5, 4, 3, 2$, and 1 for the relationships of *depends, imports, suggests, links to*, and *enhances*, respectively.

We tested a different weight scheme $(3, 2, 1, 1, 1)$ and found that the results were robust, with correlations of influence scores exceeding .95. The top packages identified were also similar. Hence, we report results based on the $(5, 4, 3, 2, 1)$ weight scheme in this paper.

For the undirected author collaboration network (e.g., Figure 4(b)), the edge between two nodes indicates that they have co-authored in at least one package. The weights of edges denote the number of packages co-authored by the corresponding two authors.

Table 2: Types of Package Dependencies.

Dependency	Definition	Frequency
Depends	B will be attached when attaching A	10523
Imports	The namespace of B will be imported when attaching A	87328
Suggests	B is used on in the examples, tests, or vignettes of A	54991
Links to	A uses the header files in B to compile its C or C++ code	5153
Enhances	B provides methods for classes in A, or helps handling objects in A	558

3.1 Measures of Influence

We focused on the following commonly used measures for evaluating node (a package or an author) influence in the one-mode network (Jain and Sinha, 2020; Morone and Makse, 2015; Salavaty et al., 2020; Wang et al., 2017):

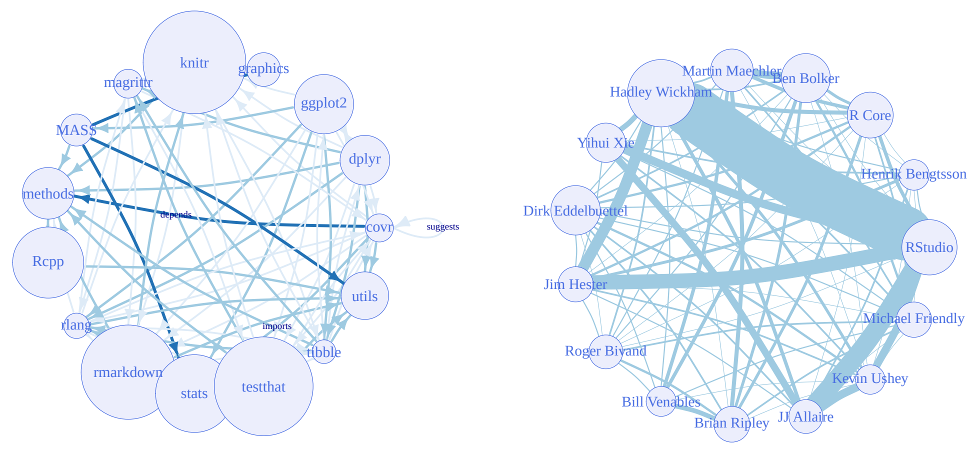
- Local structure information: Degree;
- Global structure information: Betweenness (Freeman, 1978);
- Algorithm based on random walk: Eigenvector centrality (Bonacich, 1972) and PageRank (Page et al., 1999);

Degree and In-degree Degree is the number of direct connections between nodes. For the directed package dependency network, in-degree indicates how many packages this package enhances, or is depended on, imported, suggested, or linked by. For the undirected author collaboration network, degree is the number of collaborators.

Betweenness Centrality Betweenness quantifies how important a node is as a mediator between two other nodes. Given a network, the betweenness centrality of node i can be calculated as (Freeman, 1978):

$$C_{Bet}(i) = \sum_{s \neq i \neq t} \frac{d_{s,t}(i)}{d_{s,t}} \tag{1}$$

where $d_{s,t}$ denotes the number of shortest paths from node s to node t, and $d_{s,t}(i)$ is the number of shortest paths between node s and node t going through node i.



(a) Fifteen packages with the highest in-degrees (b) Fifteen authors with the highest degrees

Figure 4: Networks of a subset of nodes with the highest degrees.

Note. The sizes of nodes represent the in-degree / degree of nodes. In the author collaboration network, the edge width reflects the weight. In the package dependency network, the color indicates the weight. "The dark edges represent *depends*, medium dark edges represent *imports*, the lightest edges represent *suggests*. Relationships of *linking to* and *enhances* are not included in this sub-graph.

Eigenvector Centrality A node with a small degree may have high eigenvector centrality (Bonacich, 1972) if it is connected with important nodes. In other words, this index considers the importance of neighbors when evaluating the centrality of a node.

Let $A = (a_{i,j})$ be the adjacency matrix of a graph, where $a_{i,j}$ represents the connection between node i and j. The eigenvector centrality of node i is given by (Bonacich, 2007):

$$C_{Eig}(i) = \frac{1}{\lambda} \sum_j a_{i,j} C_{Eig}(j) \tag{2}$$

where λ is a non-zero eigenvalue. This can also be expressed in the matrix form:

$$\lambda C_{Eig} = C_{Eig} A \tag{3}$$

where C_{Eig} is the eigenvector for the adjacency matrix A given eigenvalue λ. Bonacich (1972) suggested to choose the largest value of λ for measuring centralities.

PageRank PageRank is a variant of eigenvector centrality. It is an algorithm developed by Google to rank web pages (Page et al., 1999), and is primarily used for directed networks. Given a weighted network, it can be calculated as:

$$PR(i) = \alpha \sum_j W_{j,i} PR(j) + (1-\alpha) PR^0(i) \tag{4}$$

where $PR(i)$ and $PR(j)$ are the PageRank of node i and j, respectively. Besides, $PR^0(i)$ is typically set as $\frac{1}{N}$ where N is the number of nodes, α is the damping factor assigned to the random walk, and $W_{j,i}$ is the normalized edge weight from node j to i:

$$W_{j,i} = \frac{w_{j,i}}{\sum_t w_{j,t}} \tag{5}$$

where $w_{j,i}$ is the edge weight from node j to node i.

3.2 Bipartite Network

A bipartite network of authors and packages was built using the authorship information. The weight of an edge was assigned as 3 if the author is the maintainer of the package, and 1 otherwise (Figure 5).

Unlike the one-mode networks, which focus on either packages or authors, the bipartite network captures both the relationships between authors and packages and the collaborations among authors. As shown in Figure 6, the same author relationship configuration could be represented by two different bipartite networks. Therefore, we employed the bipartite network to gain more insights into the influential authors using the BiRank statistic.

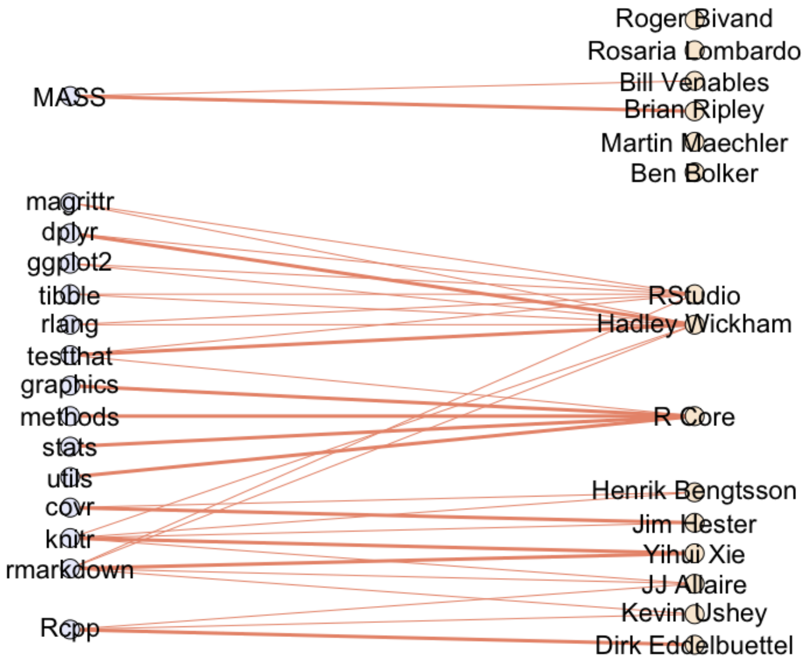


Figure 5: A Bipartite network of selected R packages and authors.

Note. Nodes on the left are 15 packages with the highest in-degrees in the package dependency network, nodes on the right are 15 authors with the highest degrees in the author collaboration network. A bold line indicates that the corresponding author is the maintainer of the corresponding package.

BiRank Aronson et al. (2020) compared different centrality measures for the bipartite network and recommended the BiRank and CoHITS indexes. For our network, the BiRank index exhibited a high correlation with the CoHITS index ($r = .860$). The top 50 authors identified by these two measures are the same, with only minor variations in their ranking. Consequently, we only reported the results of the BiRank index (He et al., 2016). Similar to PageRank, the BiRank index assumes that the ranking of nodes should be related to the ranking of the neighbors. Namely, an author would be ranked high if his or her neighbor packages are important.

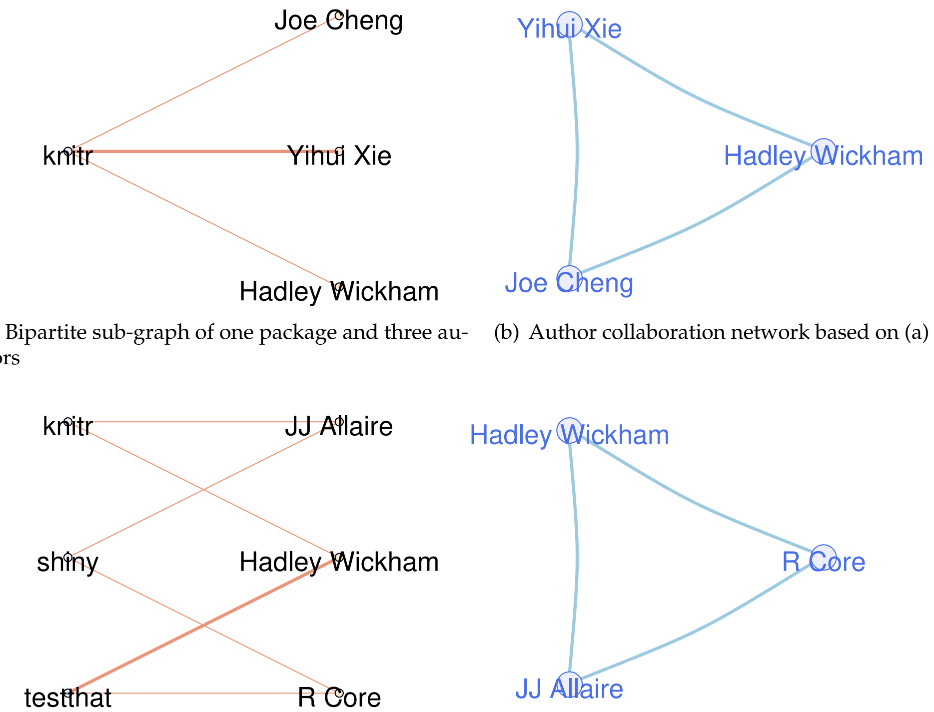
Let $A = (a_{i,j})$ be the adjacency matrix of a bipartite graph with two types of nodes $u_i(i = 1, \ldots, I)$ and $p_j(j = 1, \ldots, J)$, the BiRank value for node u_i is given by:

$$BR(u_i) = \alpha \sum_j a_{i,j} \frac{BR(p_j)}{\sqrt{C_{wDeg}(u_i)}\sqrt{C_{wDeg}(p_j)}} + (1 - \alpha) BR^0(u_i) \tag{6}$$

where $C_{wDeg}(u_i)$ and $C_{wDeg}(p_j)$ are the weighted degrees of node u_i and p_j. Similar to the PageRank index, α is the damping factor, and $BR^0(u_i)$ is the prior belief of the importance of node u_i.

3.3 Results

The centrality measures of these three networks were calculated using the R package **igraph** (Csárdi et al., 2006), **influential** (Salavaty et al., 2020), and **birankr** (Aronson and Yang, 2020).



(a) Bipartite sub-graph of one package and three authors

(b) Author collaboration network based on (a)

(c) Bipartite sub-graph of three packages and authors

(d) Author collaboration network based on (c)

Figure 6: Relationships between the bipartite network and the author collaboration network.

Package Dependency Network Table A1 presents the top 50 packages according to various centrality measures. Results show that the number of packages depending (i.e., depends, imports, suggests, linking to, or reverse enhances) on **knitr** is the greatest. This is probably because **knitr** package can help generate R package vignettes, and is therefore suggested by numerous packages. In other words, these packages are using **knitr** in developing and publishing the package, instead of extending its functionality. Additionally, **knitr** is a comprehensive package related to the topic of *Data Visualization, Result Presentation, and Interactive Web Applications*. It can help generate dynamic reports. Many packages of this topic were built based on **knitr**, such as **bookdown** for writing books and technical documents. The package with the highest betweenness (**ggplot2**) also suggests **knitr**. Compared to **knitr**, **ggplot2** demonstrates greater influence as a mediation package. It suggests and imports many important R packages, and is also depended by numerous packages. Unlike the degree and betweenness centralities, the PageRank index by considering the importance of neighbor nodes prioritizes some packages with relatively low connections. For example, the ranking of **tools** (a base R package) is 55 using in-degree, while 8 using PageRank. This is because **tools** is imported by some influential packages such as **rmarkdown** and **shiny**.

Among these influential packages in Table A1, 54 packages are ranked as top 50 by at least two indexes (Table A2), including 10 out of the 29 base and recommended R packages.

Apart from the base and recommended R packages, other important CRAN packages concentrate mainly on three topics: *Data Import, Export, and Wrangling* (e.g., **dplyr**, **tibble**, **tidyr**, **data.table**, **readr**), *Data Visualization, Result Presentation, and Interactive Web Applications* (e.g., **knitr**, **ggplot2**, **rmarkdown**, and *Supporting Packages* (e.g., **testthat**, **purrr**). Other packages are related to topics like *Computational Efficiency* (e.g., **Rcpp**, **RcppArmadillo**), *Probability Distributions* (e.g., **mvtnorm**), *Bayesian Estimation and Network Analysis* (e.g., **igraph**), and *Access to Web and Services* (e.g., **httr**). These packages are ranked as top influential packages, likely because they provide basic and comprehensive functions for important topics. A lot of packages have been developed for specific goals based on them. For example, **ggplot2** is a well-known package for data visualization. Many packages were developed based on **ggplot2** to enhance its visualization functionality, like **ggROC** specifically for plotting ROC curve, and **ggbreak** for setting axis breaks.

We also investigated the relationships between the influence scores and the number of downloads of packages. The downloads of CRAN packages on the RStudio mirror from 2021-11-01 to 2022-10-31 were obtained using the **cranlogs** (Csárdi, 2019) package. Note that the base and recommended R packages were not included when measuring downloads since they are part of R installation. The correlations of the downloads and the five indexes range from $.337 - .465$.

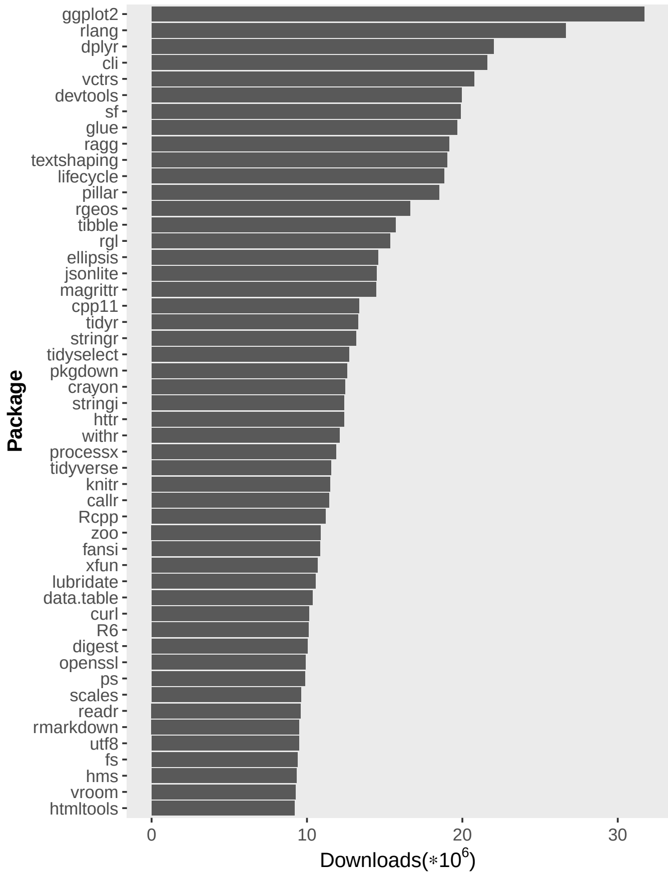


Figure 7: Top 50 packages downloaded on the RStudio mirror from 2021-11-01 to 2022-10-31.

Author Collaboration Network Table A3 lists the top 50 authors ranked by various indexes. RStudio is identified as the most influential author according to eigenvector and PageRank. Hadley Wickham and R Core demonstrated greatest influence based on degree and betweenness, respectively. Table A4 shows that 46 authors are ranked among the top 50 by at least two indexes, including organizations such as R Core, RStudio, and Google Inc., as well as individual scientists affiliated with these organizations. Figure 5 reveals that, unlike the base packages, most organizational authors of CRAN packages are not maintainers or creators. Instead, organizations such as RStudio acts as copyright holders and funders, and the R Core team often works as a contributor.

The results also suggest that different indexes prioritize different aspects of influence. Authors with limited but influential collaborators may not rank among the top 50 based on the degree centrality, but can be revealed using the eigenvector centrality and PageRank (Table A3).

Table A4 presents the top downloaded packages of influential authors. Many packages have been identified as the influential packages listed in Table A1. Figure 8 shows the collaboration heatmap among these authors, revealing intensive collaboration among influential organizations and authors. The heatmap shows three main clusters of author collaboration. Most authors at the upper left corner of the heatmap (e.g., Dirk Eddelbuettel) have the same two packages **DescTools** (an R package for descriptive statistics) and **fortunes** (an R package of collected wisdom from the R community). Their co-authored packages are mainly about two main topics on *Data Import, Export, and Wrangling* (e.g., **data.table**, **MASS**) and *Data Visualization* (e.g., **rgl**, **plotrix**). Authors in the middle of the figure are clustered together because they co-authored the **broom** package, a package for converting objects into tidy tibbles. Authors in the lower-right corner of the matrix co-authored many packages related to the *Data Visualization, Result Presentation, and Interactive Web Applications* topic (e.g., **knitr**, **bookdown**, **shiny**), many of whom are from RStudio. These results align with to the finding in the package dependency network that many influential packages are related to the *Data Import, Export, and Wrangling* and *Data Visualization, Result Presentation, and Interactive Web Applications* topics.

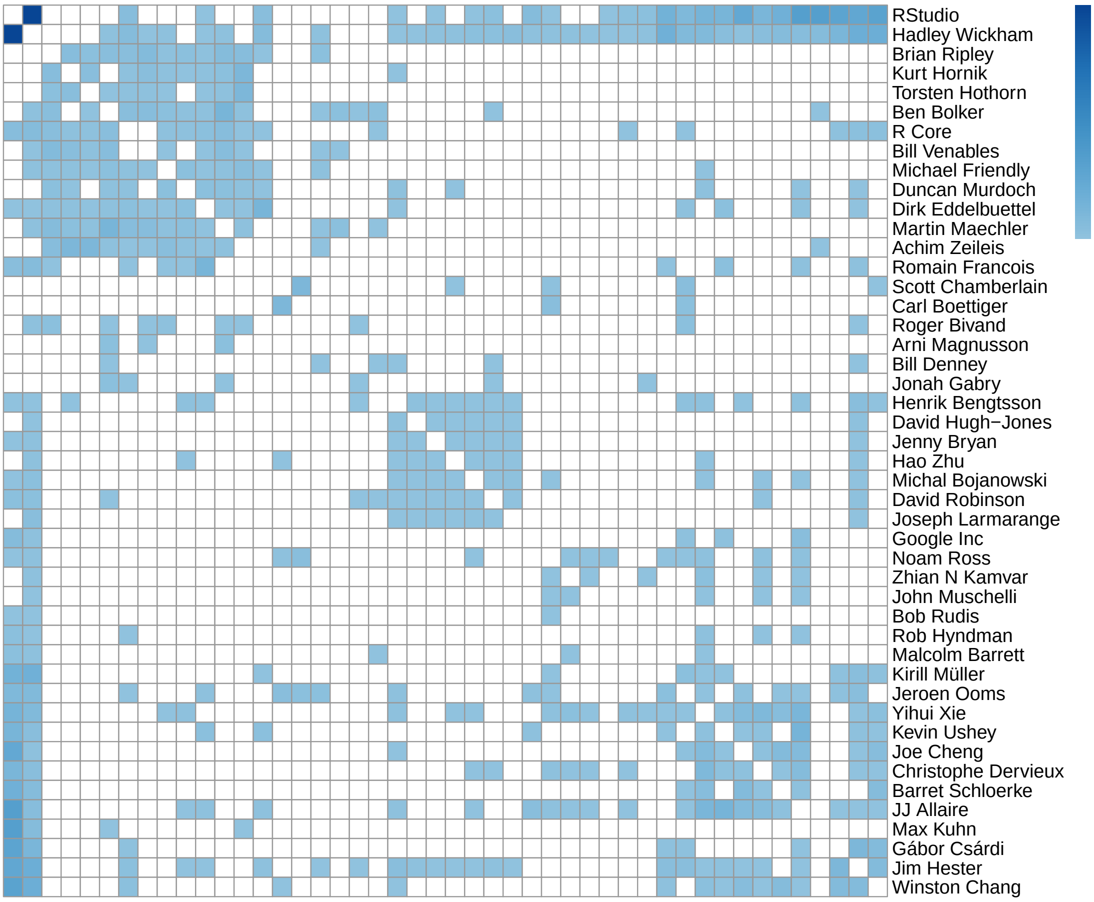


Figure 8: Collaboration heatmap of the influential authors identified in the collaboration network. *Note.* Color denotes the number of co-authored packages between two authors.

Bipartite Network The BiRank values demonstrate small to medium correlations with the indexes used in the one-mode author collaboration network ($r = .179 - .427$). The top 50 influential authors and their ranking are different from the results of the author collaboration network. Twenty-three of the top 50 authors are not ranked as top 50 by any index in the collaboration network (Table A5). Compared to the influential authors in the collaboration network, these 23 authors' packages have relatively few number of authors. But the number of their packages is high.

The most influential author identified by BiRank is Dirk Eddelbuettel, followed by Hadley Wickham, RStudio, Stéphane Laurent, and Scott Chamberlain. By contrast, in the one-mode network, Stéphane Laurent is not in the top 50 author lists based on degree, betweenness, and eigenvector. Scott Chamberlain is also not in the top 50 author lists based on degree and eigenvector. This is because many of their packages are solo-authored (e.g., **crul**). These results suggested that the bipartite network can identify productive and influential authors even without a high number of collaborators.

4 Discussion

The growing usage of R in data science is tightly associated with the increasing growth of the R ecosystem. With the rich amount of information on CRAN, this paper shows the main trends among the R developers and their packages.

Based on the package descriptions, we investigated the popular topics in the R ecosystem. Results identified a wide range of topics including various statistical methods (e.g., Cluster Analysis, Machine Learning, Bayesian Estimation, and Network Analysis) across different fields (e.g., Genetics, Environmetrics, Multivariate Analysis, and Psychometrics). Moreover, there were also packages for providing data sets, helping access to websites and online services, and improving computational efficiency. Some of these 19 topics are similar to the topics identified in the data science curricula (Zhang and Zhang, 2021) including *Machine Learning* and *Data Visualization, Result Presentation, and Interactive Web Applications*.

Using network analysis, we explored the influential packages and authors based on package dependencies and authorships. The results highlighted the crucial role of the base and recommended R packages in developing R packages, with 12 out of the 29 base and recommended packages ranked in the top 50 by at least two indexes. In addition to the packages shipped alongside base R, we also identified some important CRAN packages that support the development of R in various topics. Many influential packages were related to *Data Visualization, Result Presentation, and Interactive Web Applications* and *Data Import, Export, and Wrangling* topics. These results were similar to the finding that influential authors co-developed many important packages of these two topics.

Our findings also indicated that the contributors of R, developing from the R Core team, now have become a worldwide community, and some of them are organizations. Many of these influential authors are from RStudio or the R Core team and lead the development across many topics. For example, Yihui Xie, the creator of **knitr** and many R markdown-related packages, facilitates the development of reproducible research. While some of these influential contributors are from central positions in the author collaboration network, we also identified many productive authors with relatively few collaborators through the bipartite network of packages and authors.

4.1 Limitations and Future Directions

There are a few of limitations in the current work. First, we investigated the influential packages from the perspective of the developer community rather than the user community. To illustrate, we focused on identifying which packages are used by other packages (i.e., in the package dependency network). However, packages with high influence for developers may differ from those for the user community. Future studies are needed to explore important packages based on the usage data (e.g., citations, number of times mentioned on Twitter). Second, package dependency relationships cannot distinguish between dependencies required for publishing the package, such as vignette generation, and those needed for developing utilities. To better understand the relationships of packages based on their functionality, future study can explore the similarity between packages based on text analysis of reference manuals or vignettes. Third, we only included the R packages on CRAN or embedded in the R source code. There has already been a trend of releasing packages on GitHub and R-universe (a personal R package repository). Numerous GitHub packages and their information (e.g., contributors, commits, stars, forks) could be a rich resource for future research to understand the development and importance of R packages. Forth, as suggested by a referee, future studies can compare R and other software communites (e.g., Python). Fifth, this paper was limited by the timing of data extraction and did not include the state of the R community in the past. Future research are suggested to conduct longitudinal analysis of the R community to understand how it developed over time.

This paper also provides directions for the development of an R package recommendation system. As Silge et al. (2018) suggested, with the growth of the R ecosystems, it becomes difficult for the users to search for specific packages on CRAN. The flat organization of R packages, as well as the sorting system based on name or the date of publication, pose a big challenge for searching. It has been proposed to add keywords or tags for packages to help organize and search packages (Silge et al., 2018). Based on the results of the current paper, future research is suggested to develop a package recommendation system using the information on CRAN. Specifically, the topic modeling can help identify packages related to different topics and could also be an effective way for automatically tagging. Network analysis can also help understand the relationships among packages. Methods based on network analysis such as latent space modeling may help quantify the closeness of two packages and provide recommendations.

4.2 Concluding Remarks

This paper depicts a general picture of the R developer community based on information on CRAN. Results identified the popular topics of the R ecosystem. Investigation of influential packages and authors also contributes to the understanding of the development of the R community. It is the efforts from these experts with various backgrounds that lead to the prosperity of the R ecosystem. Moreover, results of the current study highlight the direction for developing a package recommendation system.

4.3 Acknowledgment

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1 Appendix

Table A1: Top 50 packages identified based on different network statistics of the package dependency network.

Rank	In-degree	Betweenness	Eigenvector	PageRank
1	knitr	ggplot2	knitr	testthat
2	testthat	knitr	rmarkdown	utils
3	rmarkdown	broom	testthat	methods
4	stats	dplyr	stats	stats
5	Rcpp	emmeans	ggplot2	knitr
6	ggplot2	testthat	dplyr	patchSynctex
7	methods	shiny	methods	rmarkdown
8	dplyr	stats	utils	tools
9	utils	rmarkdown	Rcpp	covr
10	graphics	survival	rlang	stringr
11	MASS	bayestestR	magrittr	graphics
12	magrittr	sf	tibble	mapmisc
13	covr	gap	tidyr	Rcpp
14	rlang	MASS	graphics	tis
15	tibble	targets	covr	grDevices
16	tidyr	caret	stringr	rlang
17	stringr	multcomp	purrr	MASS
18	grDevices	Hmisc	MASS	ggplot2
19	purrr	texreg	grDevices	magrittr
20	parallel	insight	data.table	withr
21	Matrix	parameters	jsonlite	jsonlite
22	data.table	enrichwith	Matrix	parallel
23	jsonlite	cops	shiny	htmltools
24	RcppArmadillo	mlr	parallel	scales
25	shiny	zoo	httr	fastcluster
26	httr	earth	glue	enrichwith
27	mvtnorm	tibble	scales	cops
28	survival	AER	sf	QuasiSeq
29	foreach	lme4	readr	tibble
30	scales	jsonlite	lubridate	dplyr
31	plyr	robustbase	igraph	lattice
32	igraph	plotmo	reshape2	plyr
33	reshape2	quantreg	withr	R6
34	lubridate	effects	gridExtra	vctrs
35	doParallel	rgl	foreach	reshape
36	grid	nnet	cli	glue
37	sp	nlme	tidyselect	digest
38	gridExtra	sp	plyr	tinytest
39	readr	doParallel	xml2	RUnit
40	spelling	surveillance	sp	httr
41	lattice	mice	plotly	Matrix
42	glue	Matrix	grid	xml2
43	RColorBrewer	data.tree	survival	shiny
44	sf	car	lme4	curl
45	xml2	spelling	vctrs	rstudioapi
46	raster	metafor	lifecycle	cli
47	zoo	marginaleffects	broom	yaml
48	markdown	gtools	mvtnorm	survival
49	R6	partykit	RcppArmadillo	markdown
50	glmnet	hunspell	doParallel	htmlwidgets

Table A2: Packages identified by at least two indexes.

Package	Title	Maintainer
knitr	A General-Purpose Package for Dynamic Report Generation in R	Yihui Xie
ggplot2	Create Elegant Data Visualisations Using the Grammar of Graphics	Thomas Lin Pedersen
testthat	Unit Testing for R	Hadley Wickham
rmarkdown	Dynamic Documents for R	Yihui Xie
utils*	The R Utils Package	R Core
broom	Convert Statistical Objects into Tidy Tibbles	Simon Couch
methods*	Formal Methods and Classes	R Core
stats*	The R Stats Package	R Core
dplyr	A Grammar of Data Manipulation	Hadley Wickham
Rcpp	Seamless R and C++ Integration	Dirk Eddelbuettel
shiny	Web Application Framework for R	Winston Chang
covr	Test Coverage for Packages	Jim Hester
grDevices*	The R Graphics Devices and Support for Colours and Fonts	R Core
survival	Survival Analysis	Terry M Therneau
rlang	Functions for Base Types and Core R and 'Tidyverse' Features	Lionel Henry
stringr	Simple, Consistent Wrappers for Common String Operations	Hadley Wickham
MASS*	Support Functions and Datasets for Venables and Ripley's MASS	Brian Ripley
magrittr	A Forward-Pipe Operator for R	Lionel Henry
sf	Simple Features for R	Edzer Pebesma
tibble	Simple Data Frames	Kirill Müller
tidyr	Tidy Messy Data	Hadley Wickham
graphics*	The R Graphics Package	R Core
purrr	Functional Programming Tools	Lionel Henry
parallel*	Support for Parallel Computation	R Core
data.table	Extension of 'data.frame'	Matt Dowle
withr	Run Code 'With' Temporarily Modified Global State	Lionel Henry
Matrix*	Sparse and Dense Matrix Classes and Methods	Martin Maechler
jsonlite	A Simple and Robust JSON Parser and Generator for R	Jeroen Ooms
enrichwith	Methods to Enrich R Objects with Extra Components	Ioannis Kosmidis
cops	Cluster Optimized Proximity Scaling	Thomas Rusch
RcppArmadillo	Rcpp' Integration for the 'Armadillo' Templated Linear Algebra Library	Dirk Eddelbuettel
scales	Scale Functions for Visualization	Hadley Wickham
zoo	S3 Infrastructure for Regular and Irregular Time Series (Z's Ordered Observations)	Achim Zeileis
httr	Tools for Working with URLs and HTTP	Hadley Wickham
glue	Interpreted String Literals	Jennifer Bryan
mvtnorm	Multivariate Normal and t Distributions	Torsten Hothorn
foreach	Provides Foreach Looping Construct	Folashade Daniel
lme4	Linear Mixed-Effects Models using 'Eigen' and S4	Ben Bolker
readr	Read Rectangular Text Data	Jennifer Bryan
lubridate	Make Dealing with Dates a Little Easier	Vitalie Spinu
plyr	Tools for Splitting, Applying and Combining Data	Hadley Wickham
igraph	Network Analysis and Visualization	Tamás Nepusz
lattice*	Trellis Graphics for R	Deepayan Sarkar
reshape2	Flexibly Reshape Data: A Reboot of the Reshape Package	Hadley Wickham
R6	Encapsulated Classes with Reference Semantics	Winston Chang
gridExtra	Miscellaneous Functions for "Grid" Graphics	Baptiste Auguie
vctrs	Vector Helpers	Lionel Henry
doParallel	Foreach Parallel Adaptor for the 'parallel' Package	Folashade Daniel
grid*	The Grid Graphics Package	R Core
cli	Helpers for Developing Command Line Interfaces	Gábor Csárdi
sp	Classes and Methods for Spatial Data	Edzer Pebesma
xml2	Parse XML	Hadley Wickham
spelling	Tools for Spell Checking in R	Jeroen Ooms
markdown	Render Markdown with 'commonmark'	Yihui Xie

Note. *Base and recommended R packages are part of R source code.

Table A3: Top 50 authors identified based on different network statistics of the author collaboration network.

Rank	Degree	Betweenness	Eigenvector	PageRank
1	Hadley Wickham	R Core	RStudio	RStudio
2	RStudio	Hadley Wickham	Hadley Wickham	Hadley Wickham
3	Dirk Eddelbuettel	Dirk Eddelbuettel	Jim Hester	R Core
4	Ben Bolker	Martin Maechler	JJ Allaire	Martin Maechler
5	R Core	RStudio	Winston Chang	Ben Bolker
6	Martin Maechler	Ben Bolker	Yihui Xie	Dirk Eddelbuettel
7	Yihui Xie	Kurt Hornik	Joe Cheng	Yihui Xie
8	Brian Ripley	Brian Ripley	Max Kuhn	Achim Zeileis
9	Michael Friendly	Roger Bivand	Gábor Csárdi	JJ Allaire
10	Jim Hester	Achim Zeileis	Lionel Henry	Kurt Hornik
11	Roger Bivand	Scott Chamberlain	Kirill Müller	Brian Ripley
12	JJ Allaire	Jeroen Ooms	Kevin Ushey	Roger Bivand
13	Henrik Bengtsson	Yihui Xie	Christophe Dervieux	Jim Hester
14	Bill Venables	Zhian N Kamvar	Barret Schloerke	Jeroen Ooms
15	Kevin Ushey	Michael Friendly	Jennifer Bryan	Scott Chamberlain
16	Achim Zeileis	John Muschelli	Jeroen Ooms	Michael Friendly
17	Kurt Hornik	Rob Hyndman	Carson Sievert	Zhian N Kamvar
18	Max Kuhn	Tyler Rinker	Javier Luraschi	Winston Chang
19	Romain Francois	Bill Denney	Romain Francois	Joe Cheng
20	Duncan Murdoch	John Wiseman	Daniel Falbel	Henrik Bengtsson
21	Zhian N Kamvar	Thomas Lumley	PBC	Bob Rudis
22	David Robinson	Jim Hester	R Core	Kevin Ushey
23	Hao Zhu	Sahir Bhatnagar	Henrik Bengtsson	Duncan Murdoch
24	Michal Bojanowski	Henrik Bengtsson	Ben Bolker	Max Kuhn
25	Joe Cheng	Toby Hocking	David Robinson	Bill Venables
26	Vilmantas Gegzna	Carl Boettiger	Michal Bojanowski	John Muschelli
27	Christophe Dervieux	Kevin Ushey	Thomas Lin Pedersen	Gábor Csárdi
28	Bill Denney	Kirill Müller	Davis Vaughan	Rob Hyndman
29	Adrian Baddeley	Bob Rudis	JooYoung Seo	Torsten Hothorn
30	Jeroen Ooms	Cleve Moler	Atsushi Yasumoto	Kirill Müller
31	Hong Ooi	JJ Allaire	Yixuan Qiu	Noam Ross
32	Noam Ross	Noam Ross	Joseph Larmarange	Romain Francois
33	David Hugh-Jones	Bill Venables	Dirk Eddelbuettel	Christophe Dervieux
34	Joseph Larmarange	Max Kuhn	Malcolm Barrett	Carl Boettiger
35	John Muschelli	Ben Goodrich	Noam Ross	David Robinson
36	Jonah Gabry	Jonah Gabry	Jeff Allen	Jonah Gabry
37	Malcolm Barrett	Christophe Dutang	Hao Zhu	Maëlle Salmon
38	Greg Snow	Torsten Hothorn	Michael Friendly	Michael Sumner
39	Jim Lemon	Winston Chang	Jenny Bryan	Barret Schloerke
40	Alessandro Gasparini	Kosuke Imai	Google Inc	Stéphane Laurent
41	Eduard Szoecs	Apache Foundation	David Hugh-Jones	Bill Denney
42	Tal Galili	Arni Magnusson	jQuery Foundation	Edzer Pebesma
43	Jenny Bryan	Romain Francois	Roger Bivand	Hao Zhu
44	Torsten Hothorn	Joe Cheng	Hiroaki Yutani	Indrajeet Patil
45	Matthieu Stigler	Duncan Murdoch	Martin Maechler	Michel Lang
46	Garrick Aden-Buie	Steven G Johnson	Alex Hayes	Michal Bojanowski
47	Dieter Menne	Yuan Tang	Mango Solutions	John Fox
48	Frank E Harrell Jr	Jacob Bien	Richard Iannone	Google Inc
49	Rolf Turner	Lampros Mouselimis	Simon Couch	Arni Magnusson
50	Michael Chirico	Yi Yang	Frederik Aust	Uwe Ligges

Table A4: Authors identified by at least two indexes.

Author	His or Her top downloaded packages
Hadley Wickham	ggplot2, rlang, dplyr, cli, vctrs
R Core	rgl, fansi, testthat, pkgload, car
RStudio	ggplot2, rlang, dplyr, cli, vctrs
Dirk Eddelbuettel	rgl, Rcpp, data.table, digest, nloptr
Jim Hester	devtools, glue, cpp11, withr, knitr
Ben Bolker	rgl, broom, lme4, car, gtools
Martin Maechler	lme4, car, bitops, MatrixModels, mvtnorm
JJ Allaire	knitr, Rcpp, rmarkdown, rstudioapi, shiny
Winston Chang	ggplot2, devtools, withr, processx, callr
Yihui Xie	knitr, xfun, rmarkdown, htmltools, yaml
Kurt Hornik	digest, colorspace, nloptr, e1071, tseries
Joe Cheng	knitr, rmarkdown, htmltools, bslib, sass
Brian Ripley	nloptr, car, bit, quantreg, MASS
Max Kuhn	broom, generics, caret, recipes, hardhat
Achim Zeileis	zoo, colorspace, car, lmtest, quantreg
Michael Friendly	knitr, car, maptools, DescTools, vcd
Roger Bivand	sf, rgeos, broom, sp, maptools
Gábor Csárdi	cli, rgl, crayon, processx, callr
Scott Chamberlain	plotly, crul, httpcode, jqr, bibtex
Kirill Müller	dplyr, cli, sf, pillar, tibble
Jeroen Ooms	sf, rgl, jsonlite, curl, openssl
Kevin Ushey	withr, Rcpp, data.table, rmarkdown, rstudioapi
Henrik Bengtsson	knitr, digest, broom, globals, matrixStats
Christophe Dervieux	knitr, xfun, rmarkdown, sass, tinytex
Bill Venables	MASS, raster, polynom, gplots, plotrix
Zhian N Kamvar	knitr, yaml, ggrepel, adegenet, rticles
Barret Schloerke	rmarkdown, htmltools, evaluate, sass, shiny
John Muschelli	knitr, officer, rticles, riskRegression, rscopus
Rob Hyndman	rmarkdown, forecast, fracdiff, tsfeatures, tsibble
Romain Francois	tibble, knitr, Rcpp, readr, RcppEigen
Bill Denney	digest, broom, classInt, janitor, rio
Duncan Murdoch	rgl, knitr, digest, car, kableExtra
Bob Rudis	viridisLite, viridis, ggthemes, hrbrthemes, flexdashboard
David Robinson	knitr, broom, reprex, tidytext, broom.mixed
Hao Zhu	knitr, broom, kableExtra, skimr, REDCapR
Michal Bojanowski	knitr, broom, labelled, bookdown, alluvial
Carl Boettiger	rticles, EML, taxize, drat, RNeXML
Torsten Hothorn	lmtest, mvtnorm, ipred, multcomp, TH.data
Noam Ross	knitr, viridisLite, viridis, bookdown, data.tree
Joseph Larmarange	knitr, lubridate, broom, GGally, labelled
David Hugh-Jones	knitr, broom, covr, maxLik, huxtable
Malcolm Barrett	rmarkdown, broom, ggrepel, usethis, bayesplot
Jonah Gabry	broom, rstan, StanHeaders, loo, rstantools
Jenny Bryan	knitr, broom, tidyxl
Google Inc	rmarkdown, gargle, s2, odbc, tensorflow
Arni Magnusson	xtable, gplots, coda, gdata, DescTools

Table A5: Authors identified in the bipartite network and not in the author collaboration network.

Author	His or Her top downloaded packages
Jan Wijffels	imager, udpipe, cronR, taskscheduleR, opencv
Robin K S Hankin	gsl, hypergeo, elliptic, contfrac, magic
Simon Urbanek	rgl, digest, base64enc, uuid, rJava
Kartikeya Bolar	STAT, ANOVAIREVA, ANOVAShiny, ANOVAShiny2, BLRShiny
Richard Cotton	withr, knitr, assertive.properties, assertive.base, assertive
Muhammad Yaseen	PakPMICS2014HL, PakPMICS2014Wm, DiallelAnalysisR, bayesammi, baystability
Guangchuang Yu	yulab.utils, ggfun, aplot, ggplotify, tidytree
Florian Schwendinger	Rglpk, lpSolveAPI, ROI, scs, Rsymphony
Paul Murrell	colorspace, lattice, polyclip, gridGraphics, gridBase
Kisung You	Rdimtools, maotai, mclustcomp, ADMM, ROptSpace
Przemyslaw Biecek	survminer, DALEX, iBreakDown, ingredients, eurostat
Joe Thorley	chk, yesno, nlist, term, universals
Philippe Grosjean	Rcmdr, sfsmisc, pastecs, tcltk2, svDialogs
Mohamed El Fodil Ihaddaden	ggeasy, ralger, BARIS, batata, bubblyr
Karline Soetaert	shape, inline, DescTools, deSolve, rootSolve
Emil Hvitfeldt	tidytext, yardstick, parsnip, prismatic, themis
Kevin R Coombes	ClassDiscovery, oompaBase, PCDimension, oompaData, Polychrome
Matthias Kohl	DescTools, distr, distrEx, MKmisc, MKinfer
Michael Hahsler	dbscan, arules, arulesSequences, seriation, TSP
Michael Kleinsasser	AEenrich, covid19india, SEIRfansy, eSIR, FEprovideR
Robrecht Cannoodt	ggrepel, rticles, proxyC, princurve, diffusionMap
Pablo Sanchez	facebookadsR, googleadsR, pinterestadsR, linkedInadsR, campaignmanageR
Paul R Rosenbaum	sensitivityfull, sensitivitymw, sensitivitymv, sensitivitymult, exteriorMatch

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