Detecting Ransomware Addresses on the Bitcoin Blockchain using Random Forest and Self Organizing Maps

HarvardX PH125.9x Final Capstone CYO Project

Kaylee Robert Tejeda

11/11/2021

Abstract

Ransomware is a persisent and growing threat in the world of cybersecurity. A specific area of focus involves detecting and tracking payments made to ransomware operators. While many attempts towards this goal have not made use of sophisticated machine learning methods, even those that have often result in models with poor precision or other performance issues. A two-step method is developed to address the issue of false positives and improve on previous results.

Contents

Introduction

Ransomware attacks have gained the attention of security professionals, law enforcement, and financial regulatory officials.[1] The pseudo-anonymous Bitcoin network provides a convenient method for ransomware attackers to accept payments without revealing their identity or location. The victims (usually hospitals or other large organizations) come to find that much if not all of their important organizational data have been encrypted with a secret key by an unknown attacker. They are instructed to make a payment to a specific Bitcoin address before a certain deadline to have their data decrypted before being deleted permanently.

The legal and financial implications of ransomware attacks are not of concern for the purpose of this analysis. Many parties are interested in tracking illicit activity (such as ransomware payments) around the Bitcoin blockchain as soon as possible to minimize financial losses. Daniel Goldsmith explains some of the reasons and methods of blockchain analysis at Chainalysis.com.[2] A ransomware attack could be perpetrated on an illegal darknet market site, for example. The news of such an attack might not be published at all, let alone in popular media. By analyzing the transaction record with a blockchain explorer such as BTC.com, suspicious activity could be flagged in real time given a sufficiently robust model. It may, in fact, be the first public notice of such an event. Any suspicious addresses could then be blacklisted or banned from using other services.

Lists of known ransomware payment addresses have been compiled and analyzed using various methods. One well known paper entitled "BitcoinHeist: Topological Data Analysis for Ransomware Detection on the Bitcoin Blockchain"[3] will be the source of our data set and the baseline to which we will compare our results. In that paper, Akcora, et al. use Topological Data Analysis (TDA) to classify addresses on the Bitcoin blockchain into one of 28 known ransomware address groups. Addresses with no known ransomware associations are classified as "white". The blockchain is then considered as a heterogeneous Directed Acyclic Graph (DAG) with two types of nodes describing *addresses* and *transactions*. Edges are formed between the nodes when a transaction can be associated with a particular address.

Addresses on the Bitcoin network may appear many times, with different inputs and outputs each time. The Bitcoin network data has been divided into 24-hour time intervals with the UTC-6 timezone as a reference. Speed is defined as the number of blocks the coin appears in during a 24-hour period and provides information on how quickly a coin moves through the network. Speed can be an indicator of money laundering or coin mixing, as normal payments only involve a limited number of addresses in a 24 hour period, and thus have lower speeds when compared to "mixed" coins. The temporal data can also help distinguish transactions by geolocation, as criminal transactions tend to cluster in time.

With the graph defined as such, the following six numerical features[2] are associated with a given address:

1) *Income* - the total amount of coins sent to an address
2) *Neighbors* - the number of transactions that have this address as one of its output addresses
3) *Weight* - the sum of fraction of coins that reach this address from address that do not have any other inputs within the 24-hour window, which are referred to as "starter transactions"
4) *Length* - the number of non-starter transactions on its longest chain, where a chain is defined as an acyclic directed path originating from any starter transaction and ending at the address in question
5) *Count* - The number of starter addresses connected to this address through a chain
6) *Looped* - The number of starter addresses connected to this address by more than one path

These variables are defined rather abstractly, viewing the blockchain as a topological graph with nodes and edges. The rationale behind this approach is to quantify specific transaction patterns. Akcora[3] gives a thorough explanation in the original paper of how and why these features were chosen. We shall treat the features as general numerical variables and will not seek to justify their definitions. Several machine learning methods will be applied to the original data set from the paper by Akcora[3], and the results will be compared.

Data

This data set was discovered while exploring the UCI Machine Learning Repository[4] as suggested in the project instructions. The author of this report, interested in Bitcoin and other cryptocurrencies since (unsuccessfully) mining them on an ASUS netbook in rural Peru in late 2010, used *cryptocurrency* as a preliminary search term. This brought up a single data set entitled "BitcoinHeist: Ransomware Address Data Set". The data set was downloaded and the exploration began.

A summary of the data set tells the range of values and size of the sample.

address	year	day	length	weight	count	looped	neighbors	income	label
Length:2916697	Min. :2011	Min. : 1.0	Min. : 0.00	Min. : 0.0000	Min. : 1.0	Min. : 0.0	Min. : 1.000	Min. :3.000e+07	Length:2916697
Class :character	1st Qu.:2013	1st Qu.: 92.0	1st Qu.: 2.00	1st Qu.: 0.0215	1st Qu.: 1.0	1st Qu.: 0.0	1st Qu.: 1.000	1st Qu.:7.429e+07	Class :character
Mode :character	Median :2014	Median :181.0	Median : 8.00	Median : 0.2500	Median : 1.0	Median : 0.0	Median : 2.000	Median :2.000e+08	Mode :character
NA	Mean :2014	Mean :181.5	Mean : 45.01	Mean : 0.5455	Mean : 721.6	Mean : 238.5	Mean : 2.207	Mean :4.465e+09	NA
NA	3rd Qu.:2016	3rd Qu.:271.0	3rd Qu.:108.00	3rd Qu.: 0.8819	3rd Qu.: 56.0	3rd Qu.: 0.0	3rd Qu.: 2.000	3rd Qu.:9.940e+08	NA
NA	Max. :2018	Max. :365.0	Max. :144.00	Max. :1943.7488	Max. :14497.0	Max. :14496.0	Max. :12920.000	Max. :4.996e+13	NA

A listing of the first ten rows provides a sample of the features associated with each observation.

address	year	day	length	weight	count	looped	neighbors	income	label
111K8kZAEnJg245r2cM6y9zgJGHZtJPy6	2017	11	18	0.0083333	1	0	2	100050000	princetonCerber
1123pJv8jzeFQaCV4w644pzQJzVWay2zcA	2016	132	44	0.0002441	1	0	1	100000000	princetonLocky
112536im7hy6wtKbpH1qYDWtTyMRAcA2p7	2016	246	0	1.0000000	1	0	2	200000000	princetonCerber
1126eDRw2wqSkWosjTCre8cjjQW8sSeWH7	2016	322	72	0.0039063	1	0	2	71200000	princetonCerber
1129TSjKtx65E35GiUo4AYVeyo48twbrGX	2016	238	144	0.0728484	456	0	1	200000000	princetonLocky
112AmFATxzhuSpvtz1hfpa3Zrw3BG276pc	2016	96	144	0.0846140	2821	0	1	50000000	princetonLocky

This data set has 2,916,697 observations of ten features associated with a sample of transactions from the Bitcoin blockchain. The ten features include *address* as a unique identifier, the six features defined previously (*income, neighbors, weight, length, count, loop*), two temporal features in the form of *year* and *day* (of the year as 1 to 365), and a categorical feature called *label* that categorizes each address as either "white" (meaning not connected to any ransomware activity), or one of 28 known ransomware groups as identified by three independent ransomware analysis teams (Montreal, Princeton, and Padua)[3] .

The original research team downloaded and parsed the entire Bitcoin transaction graph from January 2009 to December 2018. Based on a 24 hour time interval, daily transactions on the network were extracted and the Bitcoin graph was formed. Network edges that transferred less than ฿0.3 were filtered out since ransom amounts are rarely below this threshold. Ransomware addresses are taken from three widely adopted studies: Montreal, Princeton and Padua. "White" Bitcoin addresses were capped at one thousand per day while the entire network has up to 800,000 addresses daily.[5]

Goal

The goal of this project is to apply different machine learning algorithms to the same data set used in the original paper to produce an acceptable predictive model for categorizing ransomware addresses correctly. Improving on the results of the original paper in some way, while not strictly necessary for the purposes of the project, would be a notable sign of success.

Outline of Steps Taken

1. Analyze data set numerically and visually. Notice any pattern, look for insights.
2. Binary separation using Self Organizing Maps.
3. Improved Binary separation using Random Forest.
4. Categorical classification using Self Organizing Maps.
5. Visualize clustering to analyze results further.
6. Generate Confusion Matrix to quantify results.

Table 3: Ransomware group labels and frequency counts for full data set

	x		x
montrealAPT	11	montrealRazy	13
montrealComradeCircle	1	montrealSam	1
montrealCryptConsole	7	montrealSamSam	62
montrealCryptXXX	2419	montrealVenusLocker	7
montrealCryptoLocker	9315	montrealWannaCry	28
montrealCryptoTorLocker2015	55	montrealXLocker	1
montrealDMALocker	251	montrealXLockerv5.0	7
montrealDMALockerv3	354	montrealXTPLocker	8
montrealEDA2	6	paduaCryptoWall	12390
montrealFlyper	9	paduaJigsaw	2
montrealGlobe	32	paduaKeRanger	10
montrealGlobeImposter	55	princetonCerber	9223
montrealGlobev3	34	princetonLocky	6625
montrealJigSaw	4	white	2875284
montrealNoobCrypt	483		

Data Analysis

Hardware Specification

All of the analysis in this report was conducted on a single laptop computer, a Lenovo Yoga S1 from late 2013 with the following specs:

- CPU: Intel i7-4600U @ 3.300GHz (4th Gen quad-core i7 x86_64)
- RAM: 8217MB DDR3L @ 1600 MHz (8 GB)
- OS: Slackware64-current (15.0 RC1) `x86_64-slackware-linux-gnu` (64-bit GNU/Linux)
- R version 4.0.0 (2020-04-24) – "Arbor Day" (built from source using scripts from slackbuilds.org)
- RStudio Version 1.4.1106 "Tiger Daylily" (2389bc24, 2021-02-11) for CentOS 8 (converted using `rpm2tgz`)

Data Preparation

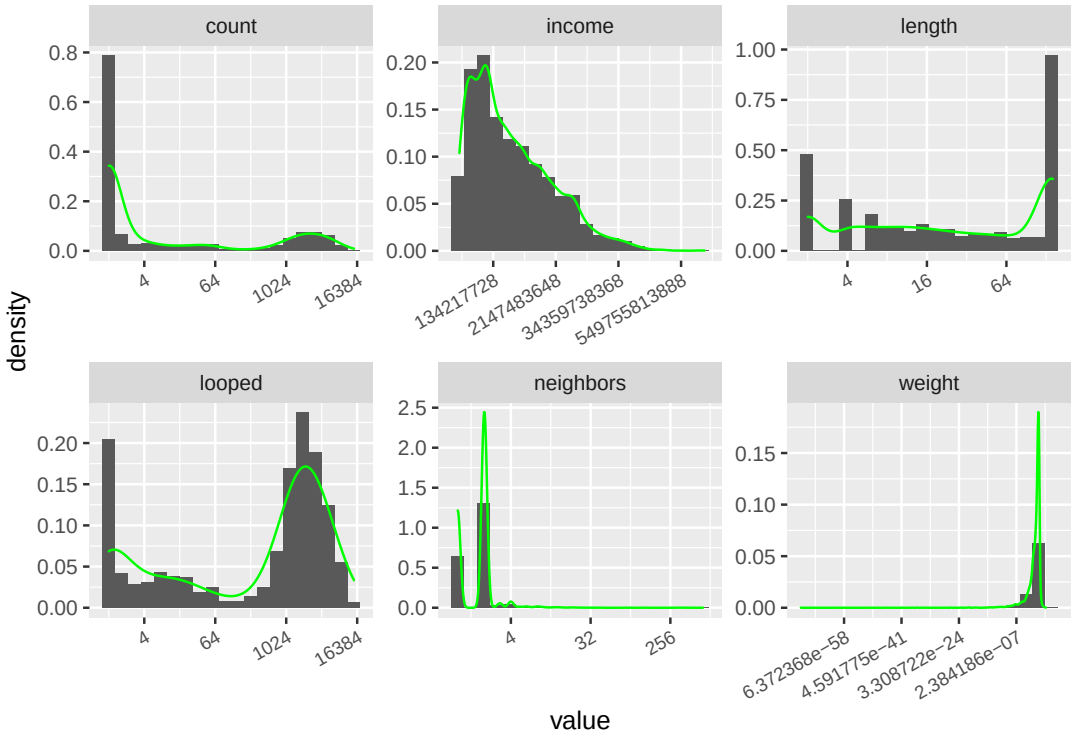
It is immediately apparent that this is a rather large data set. The usual practice of partitioning out eighty to ninety percent of the data for a training set results in a data set that is too large to process given the hardware available. For reasons that no longer apply, the original data set was first split in half with 50% reserved as "validation set" and the other 50% used as the "working set". This working set was again split in half, to give a "training set" that was of a reasonable size to deal with. At this point the partitions were small enough to work with, so the sample partitions were not further refined. This is a potential area for later optimization. Careful sampling was carried out to ensure that the ransomware groups were represented in each sample.

Exploration and Visualization

The ransomware addresses make up less than 2% of the overall data set. This presents a challenge as the target observations are sparse within the data set, especially when we consider that this is then divided into 28 subsets. In fact, some of the ransomware groups have only a single member, making categorization a dubious task. At least there are no missing values to worry about.

The proportion of ransomware addresses in the original data set is 0.0141986. The total number of NA or missing values in the original data set is 0.

Let's take a look at the distribution of the different features. Note how skewed the non-temporal features are, some of them being bimodal. Looks better on a log scale x-axis.

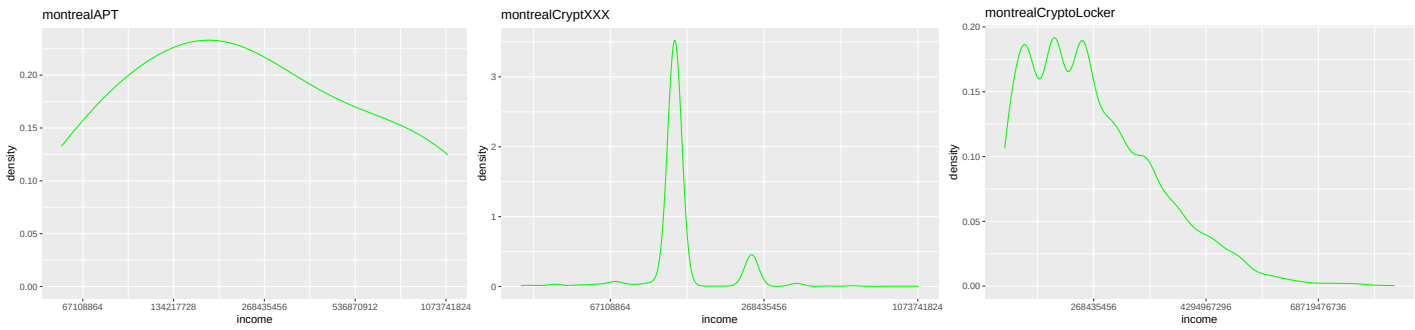


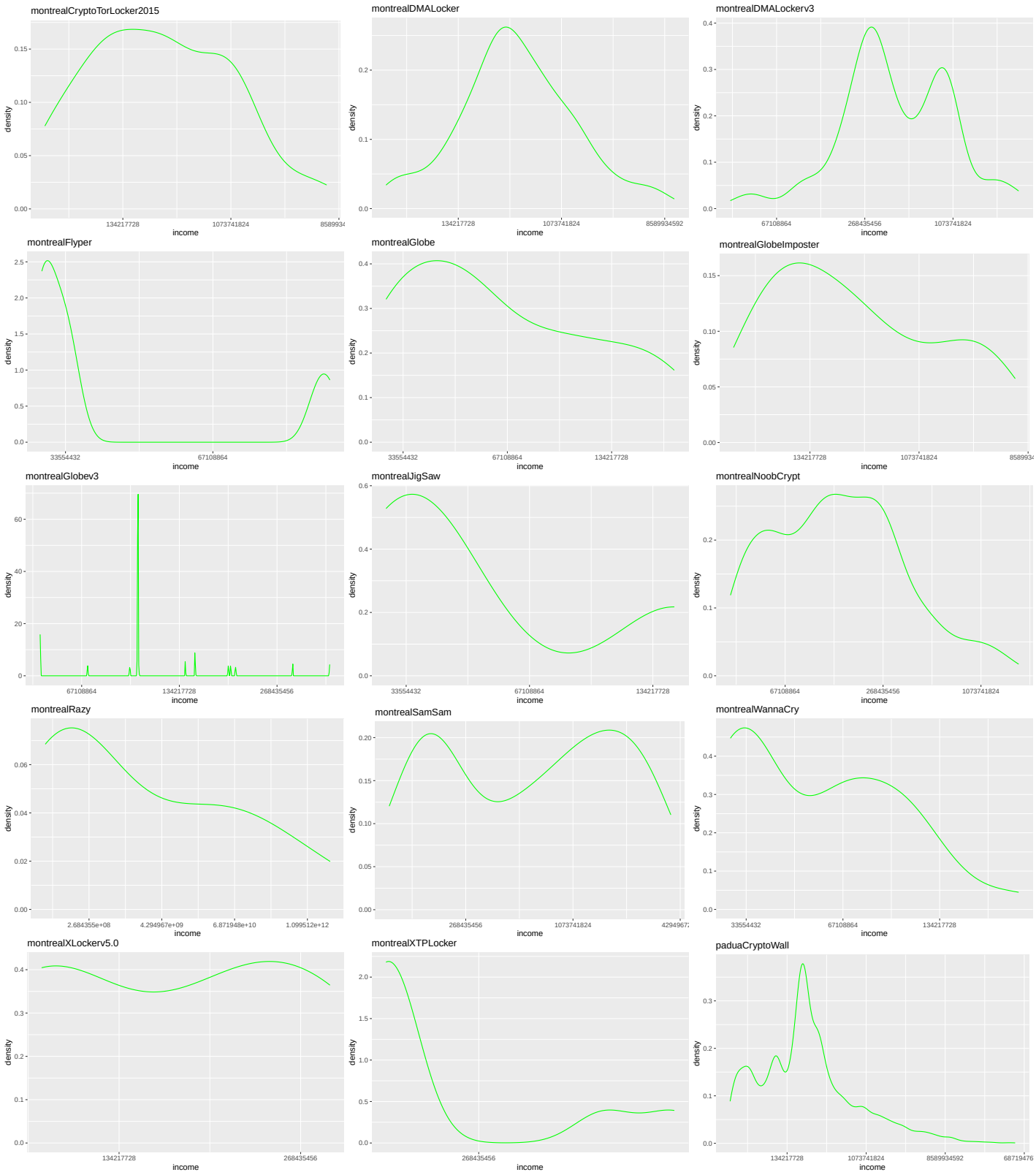
Now we can compare the relative spread of each feature by calculating the coefficient of variation for each column. Larger coefficients of variation indicate larger relative spread compared to other columns.

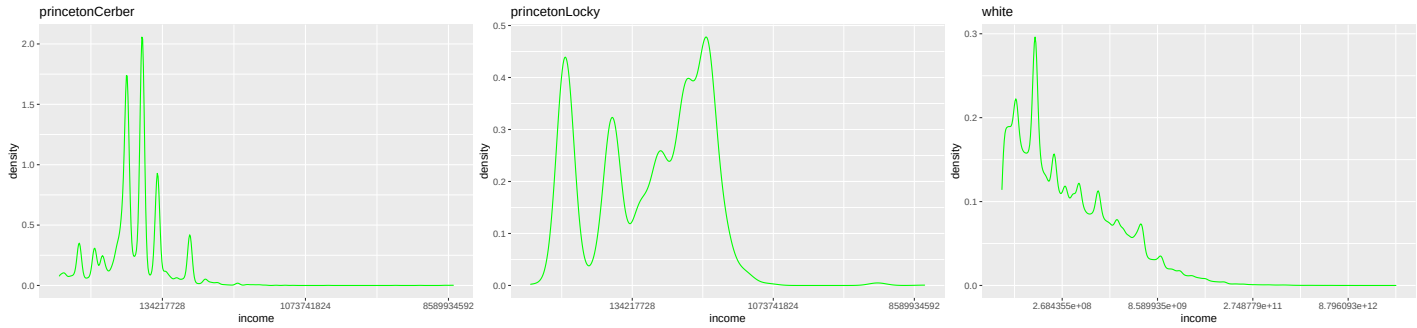
	x
income	36
neighbors	8
weight	6
length	1
count	2
looped	4

From this, it appears that income has the widest range of variability, followed by neighbors. These are also the features that are most strongly skewed to the right, meaning that a few addresses have really high values for each of these features while the bulk of the data set has very low values for these numbers.

Taking the feature with the highest variation income, let us take a look at the distribution for individual ransomware families. Perhaps there is a similarity across families.




montrealCryptoTorLocker2015
montrealDMALocker
montrealDMALockerv3
montrealFlyper
montrealGlobe
montrealGlobeImposter
montrealGlobev3
montrealJigSaw
montrealNoobCrypt
montrealRazy
montrealSamSam
montrealWannaCry
montrealXLockerv5.0
montrealXTPLocker
paduaCryptoWall
density
income



The percentage of wallets with less than one full bitcoin as their balance is 0.0134611 .

Insights Gained from Exploration

From the previous visual and statistical exploration of the data, it becomes clear what the challenge is. Ransomware related addresses are very sparse in the data set, making up less than 2% of all addresses. That small percentage is also further classified into 28 groups. Perhaps the original paper was a bit too ambitious in trying to categorize all the addresses into 29 categories, including the "white" addresses. To simplify our approach, we will categorize the addresses in a binary way, either "white" or "black", where "black" signifies an association with ransomware transactions. Asking this as a "ransomware or not-ransomware" question allows for application of methods that are known to be impractical otherwise.

Modeling approach

Akcora et al. applied a Random Forest approach to the data, however "Despite improving data scarcity, [. . .] tree based methods (i.e., Random Forest and XGBoost) fail to predict any ransomware family".[3, 11] Considering all ransomware addresses as belonging to a single group might improve the predictive power of such methods, making Random Forest worth another try.

The topological description of the data set inspired a search for topological machine learning methods, although one does not necessitate the other. Searching for *topo* in the documentation for the `caret` package [6] resulted in the entry for Self Organizing Maps, supplied by the `kohonen` package. The description at CRAN [7] was intriguing enough to merit further investigation.

Initially, the categorization of ransomware into the 28 different families was attempted using SOMs. This proved to be very resource intensive, requiring more time and RAM than was available at the time. Although it did help to illuminate how SOMs are configured, the resource requirements of the script became a deterrent. It was at this point that the SOMS were applied in a binary way, classifying all ransomware addresses as merely "black". This seemed to reduce RAM usage to the point of being feasible on the available hardware.

Being unsure of the SOM method, since it was not covered in the coursework at any point, a familiar method was sought out to compare the results to. This is when Random Forest was applied to the data set in a binary way. Much to the surprise of the author, not only did the Random Forest approach result in an acceptable model, it surpassed the model produced by the SOM approach.

The author was tempted to leave it there and write up a comparison of the two approaches to the binary problem. However, a nagging feeling that more could be done eventually inspired a second look at the categorical problem of categorizing the ransomware addresses into the 28 families. Given the high accuracy and precision of the Random Forest approach to the binary problem, it became apparent that the sparseness of the ransomware in the larger set had been eliminated completely, as had any chances of false positives. There are a few cases of false negatives, depending on how the randomization is done during the sampling process. However, the Random Forest method has never produced a false positive yet, meaning it never seems to predict a truly white address as being black. Hence, by applying the Random Forest method first, we have essentially filtered out any possibility of false positives, which is exactly what plagued the original paper by Akcora et al.[3]

Finally, a two-part method was devised to first separate the addresses into black and white groups, and then further classify the black addresses into ransomware families. Let's explore each of these separately.

Method Part 0: Binary SOMS as a first attempt to isolate ransomware addresses.

Lets see how well the SOM approach can model the data in a black/white fashion.

Here are the results of the binary SOM model.

Test set:

	black	white
black	10352	0
white	0	718810

Validation set:

	black	white
black	20704	0
white	0	1437605

This winds up being the most resource intensive and least accurate method out of those tried. It was left out of the final version of the script and is not really worth running except to compare to the next method.

Method Part 1: Binary Random Forest to isolate ransomware addresses before categorization.

A Random Forest model is trained using ten-fold cross validation and a tuning grid with the number of variables randomly sampled as candidates at each split `mtry` set to the values $= 2, 4, 6, 8, 10, 12$, each one being checked for optimization.

The confusion matrix for the test set shows excellent results, specifically in the areas of accuracy and precision.

	black	white
black	104	0
white	0	7188

Here are the overall results...

	x
Accuracy	1.0000000
Kappa	1.0000000
AccuracyLower	0.9994942
AccuracyUpper	1.0000000
AccuracyNull	0.9857378
AccuracyPValue	0.0000000
McnemarPValue	NaN

Here are the results by class...

	x
Sensitivity	1.0000000
Specificity	1.0000000
Pos Pred Value	1.0000000
Neg Pred Value	1.0000000
Precision	1.0000000
Recall	1.0000000
F1	1.0000000
Prevalence	0.0142622
Detection Rate	0.0142622
Detection Prevalence	0.0142622
Balanced Accuracy	1.0000000

The confusion matrix for the full ransomware set is very similar to that of the test set.

Here is the confusion matrix for the full ransomware data set.

	black	white
black	41355	0
white	58	2875284

Here are the big overall results....

	x
Accuracy	0.9999801
Kappa	0.9992892
AccuracyLower	0.9999743
AccuracyUpper	0.9999849
AccuracyNull	0.9858014
AccuracyPValue	0.0000000
McnemarPValue	0.0000000

Here are the big set results by class....

	x
Sensitivity	0.9985995
Specificity	1.0000000
Pos Pred Value	1.0000000
Neg Pred Value	0.9999798
Precision	1.0000000
Recall	0.9985995
F1	0.9992992
Prevalence	0.0141986
Detection Rate	0.0141787
Detection Prevalence	0.0141787
Balanced Accuracy	0.9992997

Method Part 2: Categorical SOMs to categorize predicted ransomware addresses.

Now we train a new model after throwing away all "white" addresses. The predictions from the Random Forest model are used to isolate all "black" addresses for further classification into ransomware addresses using SOMs.

When selecting the grid size for a Self Organizing Map, there are at least two different schools of thought. The two that were tried here are explained (with supporting documentation) on a Researchgate forum.[8] The first method is based on the size of the training set, and in this case results in a larger, more accurate map. The second method is based on the number of known categories to classify the data into, and in this case results in a smaller, less accurate map. For this script, a grid size of 27 has been selected.

A summary of the results for the categorization of black addresses into ransomware families follows. For the full table of predictions and statistics, see the Appendix.

Here are the overall results.

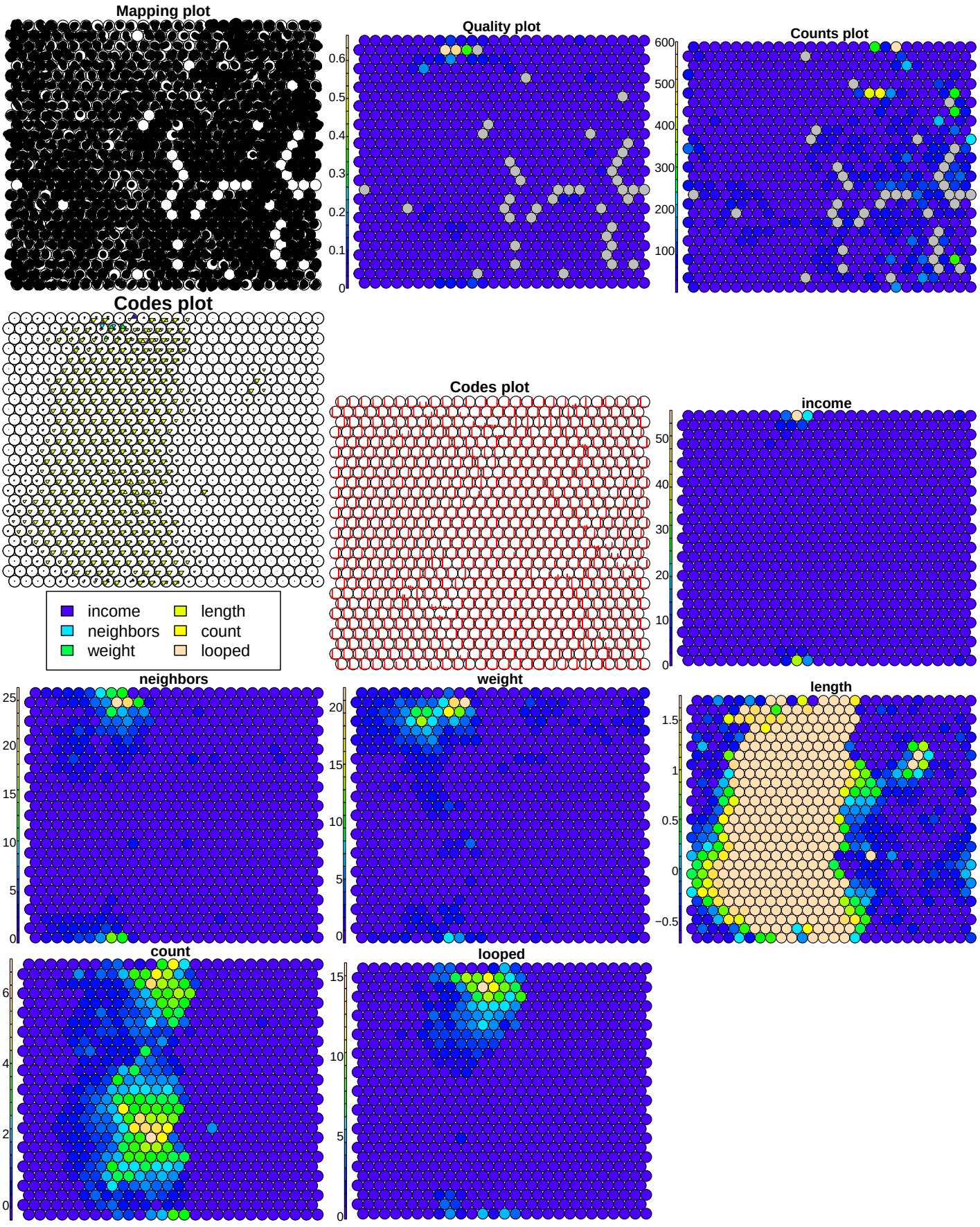
	x
Accuracy	0.9930834
Kappa	0.9911420
AccuracyLower	0.9918574
AccuracyUpper	0.9941675
AccuracyNull	0.2962999
AccuracyPValue	0.0000000
McnemarPValue	NaN

Here are the results by class.

	Sensitivity	Specificity	Pos Pred Value	Neg Pred Value	Precision	Recall	F1	Prevalence	Detection Rate	Detection Prevalence	Balanced Accuracy
Class: montrealAPT	0.0000000	1.0000000	NaN	0.9998065	NA	0.0000000	NA	0.0001935	0.0000000	0.0000000	0.5000000
Class: montrealComradeCircle	NA	1.0000000	NA	NA	NA	NA	NA	0.0000000	0.0000000	0.0000000	NA
Class: montrealCryptConsole	0.0000000	1.0000000	NaN	0.9997582	NA	0.0000000	NA	0.0002418	0.0000000	0.0000000	0.5000000
Class: montrealCryptXXX	0.9967585	0.9998971	0.9983766	0.9997943	0.9983766	0.9967585	0.9975669	0.0596856	0.0594921	0.0595889	0.9983278
Class: montrealCryptoLocker	0.9991558	0.9987451	0.9957930	0.9997488	0.9957930	0.9991558	0.9974716	0.2291657	0.2289722	0.2299395	0.9989504
Class: montrealCryptoTorLocker2015	0.4814815	0.9987408	0.3333333	0.9993216	0.3333333	0.4814815	0.3939394	0.0013059	0.0006288	0.0018863	0.7401111
Class: montrealDMALocker	0.9829060	0.9983461	0.7718121	0.9999026	0.7718121	0.9829060	0.8646617	0.0056590	0.0055623	0.0072068	0.9906261
Class: montrealDMALockerv3	1.0000000	1.0000000	1.0000000	1.0000000	1.0000000	1.0000000	1.0000000	0.0081258	0.0081258	0.0081258	1.0000000
Class: montrealEDA2	0.0000000	1.0000000	NaN	0.9998549	NA	0.0000000	NA	0.0001451	0.0000000	0.0000000	0.5000000
Class: montrealFlyper	0.0000000	1.0000000	NaN	0.9998549	NA	0.0000000	NA	0.0001451	0.0000000	0.0000000	0.5000000
Class: montrealGlobe	0.0000000	1.0000000	NaN	0.9993229	NA	0.0000000	NA	0.0006771	0.0000000	0.0000000	0.5000000
Class: montrealGlobeImposter	0.6956522	0.9992253	0.5000000	0.9996609	0.5000000	0.6956522	0.5818182	0.0011125	0.0007739	0.0015478	0.8474387
Class: montrealGlobev3	0.0588235	0.9999032	0.3333333	0.9992260	0.3333333	0.0588235	0.1000000	0.0008222	0.0000484	0.0001451	0.5293634
Class: montrealJigSaw	0.0000000	1.0000000	NaN	0.9999033	NA	0.0000000	NA	0.0000967	0.0000000	0.0000000	0.5000000
Class: montrealNoobCrypt	0.9910314	1.0000000	1.0000000	0.9999022	1.0000000	0.9910314	0.9954955	0.0107860	0.0106892	0.0106892	0.9955157
Class: montrealRazy	0.0000000	1.0000000	NaN	0.9998549	NA	0.0000000	NA	0.0001451	0.0000000	0.0000000	0.5000000
Class: montrealSam	NA	1.0000000	NA	NA	NA	NA	NA	0.0000000	0.0000000	0.0000000	NA
Class: montrealSamSam	0.1600000	0.9992736	0.2105263	0.9989833	0.2105263	0.1600000	0.1818182	0.0012092	0.0001935	0.0009190	0.5796368
Class: montrealVenusLocker	0.0000000	0.9998065	0.0000000	0.9998549	0.0000000	0.0000000	NaN	0.0001451	0.0000000	0.0001935	0.4999033
Class: montrealWannaCry	0.3125000	0.9996612	0.4166667	0.9994676	0.4166667	0.3125000	0.3571429	0.0007739	0.0002418	0.0005804	0.6560806
Class: montrealXLocker	NA	1.0000000	NA	NA	NA	NA	NA	0.0000000	0.0000000	0.0000000	NA
Class: montrealXLockerv5.0	0.0000000	1.0000000	NaN	0.9999033	NA	0.0000000	NA	0.0000967	0.0000000	0.0000000	0.5000000
Class: montrealXTPLocker	0.0000000	1.0000000	NaN	0.9998065	NA	0.0000000	NA	0.0001935	0.0000000	0.0000000	0.5000000
Class: paduaCryptoWall	0.9982044	0.9995189	0.9988566	0.9992441	0.9988566	0.9982044	0.9985304	0.2962999	0.2957678	0.2961064	0.9988616
Class: paduaJigsaw	0.0000000	1.0000000	NaN	0.9999516	NA	0.0000000	NA	0.0000484	0.0000000	0.0000000	0.5000000
Class: paduaKeRanger	0.0000000	1.0000000	NaN	0.9998065	NA	0.0000000	NA	0.0001935	0.0000000	0.0000000	0.5000000
Class: princetonCerber	1.0000000	0.9994419	0.9980250	1.0000000	0.9980250	1.0000000	0.9990115	0.2199758	0.2199758	0.2204111	0.9997210
Class: princetonLocky	0.9991085	0.9999422	0.9997026	0.9998267	0.9997026	0.9991085	0.9994055	0.1627570	0.1626119	0.1626602	0.9995253
Class: white	NA	1.0000000	NA	NA	NA	NA	NA	0.0000000	0.0000000	0.0000000	NA

Clustering Visualizations: Heatmaps and K-means clustering

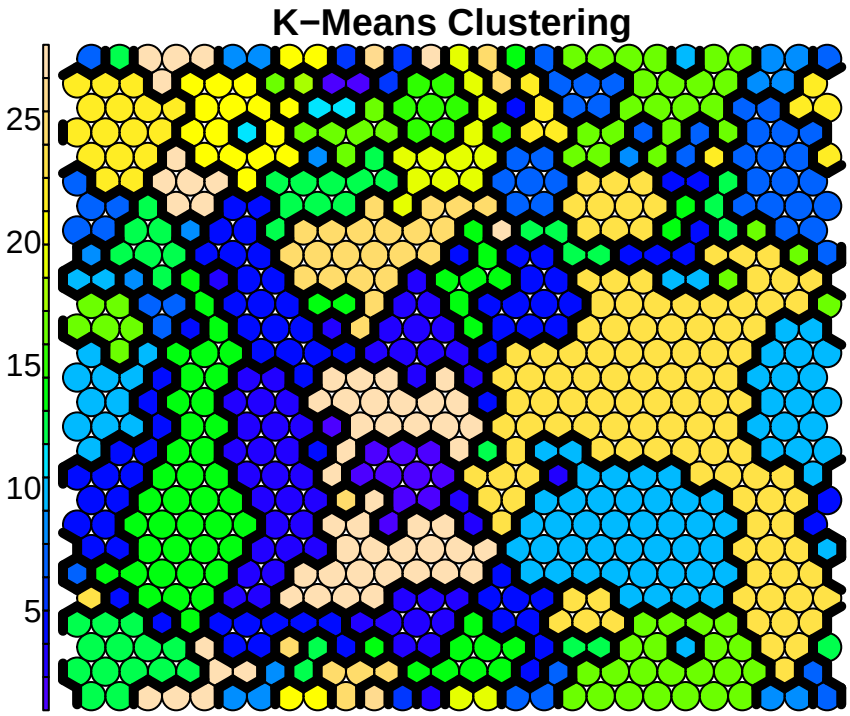
Here are some graphs, tell a bit more about them.



K-means clustering offers a nice way of visualizing the final SOM grid and the categorical boundaries that were

formed by the model.

K-means clustering categorizes the SOM grid by adding boundaries to the classification groups. This is the author's favorite graph in the entire report.



Results & Performance

Results

The first attempt to isolate ransomware using SOMs resulted in a model with an accuracy of 1 and precision 1.

The the second attempt to isolate ransomware using Random forest resulted in a model with an accuracy of 0.999980114492524 and precision 1.

Classifying the ransomware predicted by the second attempt into 28 ransomware families resulted in a model with an overall accuracy of 0.993083434099154 and minimum nonzero precision of 0.210526315789474.

Performance

The script runs on the aforementioned hardware in less than five minutes and uses less than 4GB of RAM. Given that the Bitcoin network produces one new block every ten minutes on average, then real-time analysis could theoretically be conducted on each block as it is announced using even moderate computing resources. Just for kicks, the final script was also run on a more humble computer with the following specifications:

ASUS Eee PC 1025C

- CPU: Intel Atom N2600 @ 1.600GHz (64-bit Intel Atom quad-core x86)
- RAM: 3911MB DDR3 @ 800 MT/s (4 GB)

This is a computer known for being slow and clunky. Even on this device, which runs the same operating system and software as the hardware listed previously, the total run time for the script is around 1665 seconds. At nearly 28 minutes, this is not fast enough to analyze the Bitcoin blockchain in real time, but it does show that the script can be run on very modest hardware to completion.

Pine64 Quartz64

- CPU: Rockchip RK3566 SoC aarch64 (64-bit quad-core ARM)
- RAM: DDR4 xxxxMB (8 GB)

Single board computer / Development board. This was run to benchmark a modern 64-bit ARM processor. The script runs in about xxxx minutes on this platform, just for reference.

Summary

Comparison to results from original paper

In the original paper by Akcora et al., they tested several different sets of parameters on their TDA model. According to them, "In the best TDA models for each ransomware family, we predict **16.59 false positives for each true positive**. In turn, this number is 27.44 for the best non-TDA models."[3] In fact, the highest Precision (a.k.a. Positive Predictive Value, defined as TP/(TP+FP)) they achieved was only 0.1610. By comparison, although several of our predicted classes had zero or NA precision values, the lowest non-zero precision value is 0.210526315789474, with many well above that, approaching one in a few cases.

One might say that we are comparing apples to oranges in a sense, because their method was one single model, while these results are from a two-method stack. Still, given the run time of the final script, I think the two-model approach is superior in this case, especially when measured in terms of precision and avoiding false positives.

Limitations

SOMs seem like they are easy to misconfigure. Perhaps a dual Random Forest approach would be better. this has not been attempted yet, as the two method approach presented here was satisfactory enough to present in a report.

Future Work

I only scratched he surface of the SOM algorithm which seems to have many implementations and parameters that could be investigated further and possibly optimized via cross-validation. Also, a dual Random Forest approach to first isolate the ransomware addresses and also

The script itself has a few areas that could be further optimization. The sampling method does what it needs to do, but the ratios taken for each set could possibly be optimized.

Conclusion

This paper/report presents a reliable method for classifying Bitcoin addresses into known ransomware families, while at the same time avoiding false positives by filtering them out using a binary method before classifying them further. It leaves the author of the paper wondering how much harder it would be to perform the same task for ransomware that uses privacy coins. Certain cryptocurrency networks utilize privacy coins, such as Monero, that obfuscate transactions from being analyzed in the same way that the Bitcoin network has been analyzed here. Some progress has been made towards analyzing such networks[9], but the developers of such networks continually evolve the code to complicate transaction tracking. This could be another good area for future research.

References

[1] Adam Brian Turner, Stephen McCombie and Allon J. Uhlmann (November 30, 2020) Analysis Techniques for Illicit Bitcoin Transactions

[2] Daniel Goldsmith, Kim Grauer and Yonah Shmalo (April 16, 2020) Analyzing hack subnetworks in the bitcoin transaction graph

[3] Cuneyt Gurcan Akcora, Yitao Li, Yulia R. Gel, Murat Kantarcioglu (June 19, 2019) BitcoinHeist: Topological Data Analysis for Ransomware Detection on the Bitcoin Blockchain

[4] UCI Machine Learning Repository https://archive.ics.uci.edu/ml/index.php

[5] BitcoinHeist Ransomware Address Dataset
https://archive.ics.uci.edu/ml/datasets/BitcoinHeistRansomwareAddressDataset

[6] Available Models - The `caret` package http://topepo.github.io/caret/available-models.html

[7] Ron Wehrens and Johannes Kruisselbrink, Package '`kohonen`' @ CRAN (2019) https://cran.r-project.org/web/packages/kohonen/kohonen.pdf

[8] How many nodes for self-organizing maps? (Oct 22, 2021) https://www.researchgate.net/post/How-many-nodes-for-self-organizing-maps

[9] Malte Möser, Kyle Soska, Ethan Heilman, Kevin Lee, Henry Heffan, Shashvat Srivastava, Kyle Hogan, Jason Hennessey, Andrew Miller, Arvind Narayanan, and Nicolas Christin (April 23, 2018) An Empirical Analysis of Traceability in the Monero Blockchain

Appendix:

Categorical SOM ransowmare family prediction table and confusion matrix

Here are the full prediction results for the categorization of black addresses into ransomware families. It is assumed that all white address have already been removed.

```
## Confusion Matrix and Statistics
##
##                              Reference
## Prediction                    montrealAPT montrealComradeCircle
##   montrealAPT                           0                     0
##   montrealComradeCircle                 0                     0
##   montrealCryptConsole                  0                     0
##   montrealCryptXXX                      0                     0
##   montrealCryptoLocker                  0                     0
##   montrealCryptoTorLocker2015           0                     0
##   montrealDMALocker                     2                     0
##   montrealDMALockerv3                   0                     0
##   montrealEDA2                          0                     0
##   montrealFlyper                        0                     0
##   montrealGlobe                         0                     0
##   montrealGlobeImposter                 0                     0
##   montrealGlobev3                       0                     0
##   montrealJigSaw                        0                     0
##   montrealNoobCrypt                     0                     0
##   montrealRazy                          0                     0
##   montrealSam                           0                     0
##   montrealSamSam                        2                     0
##   montrealVenusLocker                   0                     0
##   montrealWannaCry                      0                     0
##   montrealXLocker                       0                     0
##   montrealXLockerv5.0                   0                     0
##   montrealXTPLocker                     0                     0
##   paduaCryptoWall                       0                     0
##   paduaJigsaw                           0                     0
##   paduaKeRanger                         0                     0
##   princetonCerber                       0                     0
##   princetonLocky                        0                     0
##   white                                 0                     0
##                              Reference
## Prediction                    montrealCryptConsole montrealCryptXXX
##   montrealAPT                                    0                0
##   montrealComradeCircle                          0                0
##   montrealCryptConsole                           0                0
##   montrealCryptXXX                               0             1230
##   montrealCryptoLocker                           0                1
##   montrealCryptoTorLocker2015                    2                0
##   montrealDMALocker                              2                0
##   montrealDMALockerv3                            0                0
##   montrealEDA2                                   0                0
##   montrealFlyper                                 0                0
##   montrealGlobe                                  0                0
##   montrealGlobeImposter                          0                0
##   montrealGlobev3                                0                0
##   montrealJigSaw                                 0                0
```

```
##   montrealNoobCrypt                             0                0
##   montrealRazy                                  0                0
##   montrealSam                                   0                0
##   montrealSamSam                                1                0
##   montrealVenusLocker                           0                0
##   montrealWannaCry                              0                0
##   montrealXLocker                               0                0
##   montrealXLockerv5.0                           0                0
##   montrealXTPLocker                             0                0
##   paduaCryptoWall                               0                0
##   paduaJigsaw                                   0                0
##   paduaKeRanger                                 0                0
##   princetonCerber                               0                3
##   princetonLocky                                0                0
##   white                                         0                0
##                              Reference
## Prediction                    montrealCryptoLocker montrealCryptoTorLocker2015
##   montrealAPT                                    0                           0
##   montrealComradeCircle                          0                           0
##   montrealCryptConsole                           0                           0
##   montrealCryptXXX                               0                           0
##   montrealCryptoLocker                        4734                           9
##   montrealCryptoTorLocker2015                    0                          13
##   montrealDMALocker                              0                           1
##   montrealDMALockerv3                            0                           0
##   montrealEDA2                                   0                           0
##   montrealFlyper                                 0                           0
##   montrealGlobe                                  0                           0
##   montrealGlobeImposter                          0                           0
##   montrealGlobev3                                0                           0
##   montrealJigSaw                                 0                           0
##   montrealNoobCrypt                              0                           0
##   montrealRazy                                   0                           0
##   montrealSam                                    0                           0
##   montrealSamSam                                 0                           2
##   montrealVenusLocker                            0                           0
##   montrealWannaCry                               0                           0
##   montrealXLocker                                0                           0
##   montrealXLockerv5.0                            0                           0
##   montrealXTPLocker                              0                           0
##   paduaCryptoWall                                4                           2
##   paduaJigsaw                                    0                           0
##   paduaKeRanger                                  0                           0
##   princetonCerber                                0                           0
##   princetonLocky                                 0                           0
##   white                                          0                           0
##                              Reference
## Prediction                    montrealDMALocker montrealDMALockerv3
##   montrealAPT                                 0                   0
##   montrealComradeCircle                       0                   0
##   montrealCryptConsole                        0                   0
##   montrealCryptXXX                            0                   0
##   montrealCryptoLocker                        0                   0
##   montrealCryptoTorLocker2015                 0                   0
##   montrealDMALocker                         115                   0
##   montrealDMALockerv3                         0                 168
```

```
##   montrealEDA2                                0                 0
##   montrealFlyper                              0                 0
##   montrealGlobe                               0                 0
##   montrealGlobeImposter                       0                 0
##   montrealGlobev3                             0                 0
##   montrealJigSaw                              0                 0
##   montrealNoobCrypt                           0                 0
##   montrealRazy                                0                 0
##   montrealSam                                 0                 0
##   montrealSamSam                              0                 0
##   montrealVenusLocker                         0                 0
##   montrealWannaCry                            0                 0
##   montrealXLocker                             0                 0
##   montrealXLockerv5.0                         0                 0
##   montrealXTPLocker                           0                 0
##   paduaCryptoWall                             1                 0
##   paduaJigsaw                                 0                 0
##   paduaKeRanger                               0                 0
##   princetonCerber                             1                 0
##   princetonLocky                              0                 0
##   white                                       0                 0
##                              Reference
## Prediction                    montrealEDA2 montrealFlyper montrealGlobe
##   montrealAPT                            0              0             0
##   montrealComradeCircle                  0              0             0
##   montrealCryptConsole                   0              0             0
##   montrealCryptXXX                       0              0             1
##   montrealCryptoLocker                   0              0             0
##   montrealCryptoTorLocker2015            0              1             8
##   montrealDMALocker                      0              0             3
##   montrealDMALockerv3                    0              0             0
##   montrealEDA2                           0              0             0
##   montrealFlyper                         0              0             0
##   montrealGlobe                          0              0             0
##   montrealGlobeImposter                  1              0             0
##   montrealGlobev3                        0              0             1
##   montrealJigSaw                         0              0             0
##   montrealNoobCrypt                      0              0             0
##   montrealRazy                           0              0             0
##   montrealSam                            0              0             0
##   montrealSamSam                         1              1             1
##   montrealVenusLocker                    0              0             0
##   montrealWannaCry                       0              1             0
##   montrealXLocker                        0              0             0
##   montrealXLockerv5.0                    0              0             0
##   montrealXTPLocker                      0              0             0
##   paduaCryptoWall                        0              0             0
##   paduaJigsaw                            0              0             0
##   paduaKeRanger                          0              0             0
##   princetonCerber                        0              0             0
##   princetonLocky                         1              0             0
##   white                                  0              0             0
##                              Reference
## Prediction                    montrealGlobeImposter montrealGlobev3
##   montrealAPT                                     0              0
##   montrealComradeCircle                           0              0
```

```
##   montrealCryptConsole                          0              0
##   montrealCryptXXX                              0              0
##   montrealCryptoLocker                          1              0
##   montrealCryptoTorLocker2015                   3              3
##   montrealDMALocker                             0              7
##   montrealDMALockerv3                           0              0
##   montrealEDA2                                  0              0
##   montrealFlyper                                0              0
##   montrealGlobe                                 0              0
##   montrealGlobeImposter                        16              0
##   montrealGlobev3                               0              1
##   montrealJigSaw                                0              0
##   montrealNoobCrypt                             0              0
##   montrealRazy                                  0              0
##   montrealSam                                   0              0
##   montrealSamSam                                1              5
##   montrealVenusLocker                           1              1
##   montrealWannaCry                              1              0
##   montrealXLocker                               0              0
##   montrealXLockerv5.0                           0              0
##   montrealXTPLocker                             0              0
##   paduaCryptoWall                               0              0
##   paduaJigsaw                                   0              0
##   paduaKeRanger                                 0              0
##   princetonCerber                               0              0
##   princetonLocky                                0              0
##   white                                         0              0
##                             Reference
## Prediction                   montrealJigSaw montrealNoobCrypt montrealRazy
##   montrealAPT                             0                 0            0
##   montrealComradeCircle                   0                 0            0
##   montrealCryptConsole                    0                 0            0
##   montrealCryptXXX                        0                 0            0
##   montrealCryptoLocker                    0                 0            0
##   montrealCryptoTorLocker2015             1                 0            0
##   montrealDMALocker                       0                 2            0
##   montrealDMALockerv3                     0                 0            0
##   montrealEDA2                            0                 0            0
##   montrealFlyper                          0                 0            0
##   montrealGlobe                           0                 0            0
##   montrealGlobeImposter                   0                 0            1
##   montrealGlobev3                         0                 0            0
##   montrealJigSaw                          0                 0            0
##   montrealNoobCrypt                       0               221            0
##   montrealRazy                            0                 0            0
##   montrealSam                             0                 0            0
##   montrealSamSam                          1                 0            0
##   montrealVenusLocker                     0                 0            1
##   montrealWannaCry                        0                 0            1
##   montrealXLocker                         0                 0            0
##   montrealXLockerv5.0                     0                 0            0
##   montrealXTPLocker                       0                 0            0
##   paduaCryptoWall                         0                 0            0
##   paduaJigsaw                             0                 0            0
##   paduaKeRanger                           0                 0            0
##   princetonCerber                         0                 0            0
```

```
##   princetonLocky                          0                0            0
##   white                                   0                0            0
##                             Reference
## Prediction                   montrealSam montrealSamSam montrealVenusLocker
##   montrealAPT                          0              0                    0
##   montrealComradeCircle                0              0                    0
##   montrealCryptConsole                 0              0                    0
##   montrealCryptXXX                     0              0                    0
##   montrealCryptoLocker                 0              0                    0
##   montrealCryptoTorLocker2015          0              3                    3
##   montrealDMALocker                    0              9                    0
##   montrealDMALockerv3                  0              0                    0
##   montrealEDA2                         0              0                    0
##   montrealFlyper                       0              0                    0
##   montrealGlobe                        0              0                    0
##   montrealGlobeImposter                0              7                    0
##   montrealGlobev3                      0              0                    0
##   montrealJigSaw                       0              0                    0
##   montrealNoobCrypt                    0              0                    0
##   montrealRazy                         0              0                    0
##   montrealSam                          0              0                    0
##   montrealSamSam                       0              4                    0
##   montrealVenusLocker                  0              0                    0
##   montrealWannaCry                     0              2                    0
##   montrealXLocker                      0              0                    0
##   montrealXLockerv5.0                  0              0                    0
##   montrealXTPLocker                    0              0                    0
##   paduaCryptoWall                      0              0                    0
##   paduaJigsaw                          0              0                    0
##   paduaKeRanger                        0              0                    0
##   princetonCerber                      0              0                    0
##   princetonLocky                       0              0                    0
##   white                                0              0                    0
##                             Reference
## Prediction                   montrealWannaCry montrealXLocker
##   montrealAPT                               0               0
##   montrealComradeCircle                     0               0
##   montrealCryptConsole                      0               0
##   montrealCryptXXX                          0               0
##   montrealCryptoLocker                      0               0
##   montrealCryptoTorLocker2015               1               0
##   montrealDMALocker                         5               0
##   montrealDMALockerv3                       0               0
##   montrealEDA2                              0               0
##   montrealFlyper                            0               0
##   montrealGlobe                             0               0
##   montrealGlobeImposter                     3               0
##   montrealGlobev3                           0               0
##   montrealJigSaw                            0               0
##   montrealNoobCrypt                         0               0
##   montrealRazy                              0               0
##   montrealSam                               0               0
##   montrealSamSam                            0               0
##   montrealVenusLocker                       0               0
##   montrealWannaCry                          5               0
##   montrealXLocker                           0               0
```

```
##   montrealXLockerv5.0                        0              0
##   montrealXTPLocker                          0              0
##   paduaCryptoWall                            0              0
##   paduaJigsaw                                0              0
##   paduaKeRanger                              0              0
##   princetonCerber                            2              0
##   princetonLocky                             0              0
##   white                                      0              0
##                               Reference
## Prediction                     montrealXLockerv5.0 montrealXTPLocker
##   montrealAPT                                    0                 0
##   montrealComradeCircle                          0                 0
##   montrealCryptConsole                           0                 0
##   montrealCryptXXX                               0                 0
##   montrealCryptoLocker                           0                 0
##   montrealCryptoTorLocker2015                    0                 0
##   montrealDMALocker                              1                 2
##   montrealDMALockerv3                            0                 0
##   montrealEDA2                                   0                 0
##   montrealFlyper                                 0                 0
##   montrealGlobe                                  0                 0
##   montrealGlobeImposter                          1                 2
##   montrealGlobev3                                0                 0
##   montrealJigSaw                                 0                 0
##   montrealNoobCrypt                              0                 0
##   montrealRazy                                   0                 0
##   montrealSam                                    0                 0
##   montrealSamSam                                 0                 0
##   montrealVenusLocker                            0                 0
##   montrealWannaCry                               0                 0
##   montrealXLocker                                0                 0
##   montrealXLockerv5.0                            0                 0
##   montrealXTPLocker                              0                 0
##   paduaCryptoWall                                0                 0
##   paduaJigsaw                                    0                 0
##   paduaKeRanger                                  0                 0
##   princetonCerber                                0                 0
##   princetonLocky                                 0                 0
##   white                                          0                 0
##                               Reference
## Prediction                     paduaCryptoWall paduaJigsaw paduaKeRanger
##   montrealAPT                                0           0             0
##   montrealComradeCircle                      0           0             0
##   montrealCryptConsole                       0           0             0
##   montrealCryptXXX                           1           0             0
##   montrealCryptoLocker                       9           0             0
##   montrealCryptoTorLocker2015                1           0             0
##   montrealDMALocker                          0           0             0
##   montrealDMALockerv3                        0           0             0
##   montrealEDA2                               0           0             0
##   montrealFlyper                             0           0             0
##   montrealGlobe                              0           0             0
##   montrealGlobeImposter                      0           0             1
##   montrealGlobev3                            0           1             0
##   montrealJigSaw                             0           0             0
##   montrealNoobCrypt                          0           0             0
```

```
##   montrealRazy                              0           0            0
##   montrealSam                               0           0            0
##   montrealSamSam                            0           0            0
##   montrealVenusLocker                       0           0            1
##   montrealWannaCry                          0           0            2
##   montrealXLocker                           0           0            0
##   montrealXLockerv5.0                       0           0            0
##   montrealXTPLocker                         0           0            0
##   paduaCryptoWall                        6115           0            0
##   paduaJigsaw                               0           0            0
##   paduaKeRanger                             0           0            0
##   princetonCerber                           0           0            0
##   princetonLocky                            0           0            0
##   white                                     0           0            0
##                             Reference
## Prediction                   princetonCerber princetonLocky white
##   montrealAPT                              0              0     0
##   montrealComradeCircle                    0              0     0
##   montrealCryptConsole                     0              0     0
##   montrealCryptXXX                         0              0     0
##   montrealCryptoLocker                     0              0     0
##   montrealCryptoTorLocker2015              0              0     0
##   montrealDMALocker                        0              0     0
##   montrealDMALockerv3                      0              0     0
##   montrealEDA2                             0              0     0
##   montrealFlyper                           0              0     0
##   montrealGlobe                            0              0     0
##   montrealGlobeImposter                    0              0     0
##   montrealGlobev3                          0              0     0
##   montrealJigSaw                           0              0     0
##   montrealNoobCrypt                        0              0     0
##   montrealRazy                             0              0     0
##   montrealSam                              0              0     0
##   montrealSamSam                           0              0     0
##   montrealVenusLocker                      0              0     0
##   montrealWannaCry                         0              0     0
##   montrealXLocker                          0              0     0
##   montrealXLockerv5.0                      0              0     0
##   montrealXTPLocker                        0              0     0
##   paduaCryptoWall                          0              0     0
##   paduaJigsaw                              0              0     0
##   paduaKeRanger                            0              0     0
##   princetonCerber                       4548              3     0
##   princetonLocky                           0           3362     0
##   white                                    0              0     0
##
## Overall Statistics
##
##                Accuracy : 0.9931
##                  95% CI : (0.9919, 0.9942)
##     No Information Rate : 0.2963
##     P-Value [Acc > NIR] : < 2.2e-16
##
##                   Kappa : 0.9911
##
##  Mcnemar's Test P-Value : NA
```

```
##
## Statistics by Class:
##
##                      Class: montrealAPT Class: montrealComradeCircle
## Sensitivity                   0.0000000                           NA
## Specificity                   1.0000000                            1
## Pos Pred Value                      NaN                           NA
## Neg Pred Value                0.9998065                           NA
## Prevalence                    0.0001935                            0
## Detection Rate                0.0000000                            0
## Detection Prevalence          0.0000000                            0
## Balanced Accuracy             0.5000000                           NA
##                      Class: montrealCryptConsole Class: montrealCryptXXX
## Sensitivity                        0.0000000                 0.99676
## Specificity                        1.0000000                 0.99990
## Pos Pred Value                           NaN                 0.99838
## Neg Pred Value                     0.9997582                 0.99979
## Prevalence                         0.0002418                 0.05969
## Detection Rate                     0.0000000                 0.05949
## Detection Prevalence               0.0000000                 0.05959
## Balanced Accuracy                  0.5000000                 0.99833
##                      Class: montrealCryptoLocker
## Sensitivity                            0.9992
## Specificity                            0.9987
## Pos Pred Value                         0.9958
## Neg Pred Value                         0.9997
## Prevalence                             0.2292
## Detection Rate                         0.2290
## Detection Prevalence                   0.2299
## Balanced Accuracy                      0.9990
##                      Class: montrealCryptoTorLocker2015
## Sensitivity                                   0.4814815
## Specificity                                   0.9987408
## Pos Pred Value                                0.3333333
## Neg Pred Value                                0.9993216
## Prevalence                                    0.0013059
## Detection Rate                                0.0006288
## Detection Prevalence                          0.0018863
## Balanced Accuracy                             0.7401111
##                      Class: montrealDMALocker Class: montrealDMALockerv3
## Sensitivity                          0.982906                   1.000000
## Specificity                          0.998346                   1.000000
## Pos Pred Value                       0.771812                   1.000000
## Neg Pred Value                       0.999903                   1.000000
## Prevalence                           0.005659                   0.008126
## Detection Rate                       0.005562                   0.008126
## Detection Prevalence                 0.007207                   0.008126
## Balanced Accuracy                    0.990626                   1.000000
##                      Class: montrealEDA2 Class: montrealFlyper
## Sensitivity                    0.0000000             0.0000000
## Specificity                    1.0000000             1.0000000
## Pos Pred Value                       NaN                   NaN
## Neg Pred Value                 0.9998549             0.9998549
## Prevalence                     0.0001451             0.0001451
## Detection Rate                 0.0000000             0.0000000
## Detection Prevalence           0.0000000             0.0000000
```

```
## Balanced Accuracy              0.5000000             0.5000000
##                      Class: montrealGlobe Class: montrealGlobeImposter
## Sensitivity                     0.0000000                     0.6956522
## Specificity                     1.0000000                     0.9992253
## Pos Pred Value                        NaN                     0.5000000
## Neg Pred Value                  0.9993229                     0.9996609
## Prevalence                      0.0006771                     0.0011125
## Detection Rate                  0.0000000                     0.0007739
## Detection Prevalence            0.0000000                     0.0015478
## Balanced Accuracy               0.5000000                     0.8474387
##                      Class: montrealGlobev3 Class: montrealJigSaw
## Sensitivity                    5.882e-02             0.000e+00
## Specificity                    9.999e-01             1.000e+00
## Pos Pred Value                 3.333e-01                   NaN
## Neg Pred Value                 9.992e-01             9.999e-01
## Prevalence                     8.222e-04             9.674e-05
## Detection Rate                 4.837e-05             0.000e+00
## Detection Prevalence           1.451e-04             0.000e+00
## Balanced Accuracy              5.294e-01             5.000e-01
##                      Class: montrealNoobCrypt Class: montrealRazy
## Sensitivity                           0.99103           0.0000000
## Specificity                           1.00000           1.0000000
## Pos Pred Value                        1.00000                 NaN
## Neg Pred Value                        0.99990           0.9998549
## Prevalence                            0.01079           0.0001451
## Detection Rate                        0.01069           0.0000000
## Detection Prevalence                  0.01069           0.0000000
## Balanced Accuracy                     0.99552           0.5000000
##                      Class: montrealSam Class: montrealSamSam
## Sensitivity                          NA             0.1600000
## Specificity                           1             0.9992736
## Pos Pred Value                       NA             0.2105263
## Neg Pred Value                       NA             0.9989833
## Prevalence                            0             0.0012092
## Detection Rate                        0             0.0001935
## Detection Prevalence                  0             0.0009190
## Balanced Accuracy                    NA             0.5796368
##                      Class: montrealVenusLocker Class: montrealWannaCry
## Sensitivity                           0.0000000               0.3125000
## Specificity                           0.9998065               0.9996612
## Pos Pred Value                        0.0000000               0.4166667
## Neg Pred Value                        0.9998549               0.9994676
## Prevalence                            0.0001451               0.0007739
## Detection Rate                        0.0000000               0.0002418
## Detection Prevalence                  0.0001935               0.0005804
## Balanced Accuracy                     0.4999033               0.6560806
##                      Class: montrealXLocker Class: montrealXLockerv5.0
## Sensitivity                              NA                   0.000e+00
## Specificity                               1                   1.000e+00
## Pos Pred Value                           NA                         NaN
## Neg Pred Value                           NA                   9.999e-01
## Prevalence                                0                   9.674e-05
## Detection Rate                            0                   0.000e+00
## Detection Prevalence                      0                   0.000e+00
## Balanced Accuracy                        NA                   5.000e-01
##                      Class: montrealXTPLocker Class: paduaCryptoWall
```

```
## Sensitivity                          0.0000000                0.9982
## Specificity                          1.0000000                0.9995
## Pos Pred Value                             NaN                0.9989
## Neg Pred Value                       0.9998065                0.9992
## Prevalence                           0.0001935                0.2963
## Detection Rate                       0.0000000                0.2958
## Detection Prevalence                 0.0000000                0.2961
## Balanced Accuracy                    0.5000000                0.9989
##                       Class: paduaJigsaw Class: paduaKeRanger
## Sensitivity                    0.000e+00            0.0000000
## Specificity                    1.000e+00            1.0000000
## Pos Pred Value                       NaN                  NaN
## Neg Pred Value                 1.000e+00            0.9998065
## Prevalence                     4.837e-05            0.0001935
## Detection Rate                 0.000e+00            0.0000000
## Detection Prevalence           0.000e+00            0.0000000
## Balanced Accuracy              5.000e-01            0.5000000
##                       Class: princetonCerber Class: princetonLocky Class: white
## Sensitivity                           1.0000                0.9991           NA
## Specificity                           0.9994                0.9999            1
## Pos Pred Value                        0.9980                0.9997           NA
## Neg Pred Value                        1.0000                0.9998           NA
## Prevalence                            0.2200                0.1628            0
## Detection Rate                        0.2200                0.1626            0
## Detection Prevalence                  0.2204                0.1627            0
## Balanced Accuracy                     0.9997                0.9995           NA

## 4651.738 sec elapsed
```