Continuous Transparent Authentication with User-Device Physical Unclonable Functions (UD-PUFs) based on Mobile Device Touchscreen Interactions

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ABSTRACT

In this paper we discuss the problems with existing authentication schemes. We then implement a system which seeks to solve problems present in these other systems. This system uses an $n-gram$ Markov model to track properties of a user's interactions with the soft keyboard of a mobile device. This system is used to continuously compare a user's current behavior against the past behavior of that same user. We describe how our system protects against the vulnerabilities existing in current authentication systems and demonstrate the practicality of our implementation.

1. INTRODUCTION

Malicious parties attempt to gain access to data of their victims. Attackers go through the trouble of preforming these attacks because gaining access to the data might be quite lucrative. Mobile devices are often used to store credit card information, passwords, and banking information. This data can be leveraged for significant loss.

Many current practices keep mobile devices secure with a lock screen. These protection mechanisms require that the user preform some action when the mobile device state moves from inactive to active. This one-time authentication allows access to everything on the device including all applications. Significant amounts of data is hosted in various applications on mobile devices. This data could be potentially damaging to the user if it is exposed to a malicious party. The compromised information could include social security numbers, credit cards, passwords, and banking information.

The tendency for applications to remember a user's authentication information functions to make the lock screen the only line of defense in many cases. The combination of having a single authentication with a significant amount of valuable data makes mobile devices potentially very lucrative to steal. The mobile nature of these devices exacerbates the issue causes them to be extremely susceptible to theft. In fact, mobile device theft is a serious problem. Consumer Reports [1] reported over 3.1 million smart phone thefts in 2013. Federal Communications Commission (FCC)[2] in its December 2014 report estimates 368.9 phone thefts per 100000 individuals in 2013. It states that about one third of crime involves a mobile phone. There are many ways an attacker might exploit this one-time authentication in order to gain access to resources on a mobile device. There are several different types of lock screens which are commonly employed. Android Version 6.0.1 Marshmallow includes password, pin, and pattern options for securing the lock screen. Pin allows the user to create a small fixed-length sequence of numbers. Password authentication is similar to pin authentication except letters, symbols, and numbers are all used to create the secret. Swipe authentication is seemingly different allowing the user to create a pattern of swiping between 9 points on the screen. These methods are based on the user having some secret knowledge which is entered on the lock screen using the touchscreen. This authentication occurs each time the phone state changes from inactive to active.

All methods of authentication mentioned discussed thus far require that a user enter information using the touch screen each time they want to utilize their device. There are some problems with this. Malicious parties may try to exploit the requirement of entry through the touch screen by shoulder-surfing. This practice involves an attacker watching a person enter their secret so that it might be replicated later. [3] discusses the vulnerability of various touch screen input methods to shoulder-surfing attacks while [4] measured the susceptibility of users to shoulder surfing attacks observing attackers having a ($> 20\%$) success rate on Android keyboards in the reproduction of a password after 3 attempts. Smudge attacks where, oily residues are used to detect common touch screen patters, also represent a significant security risk for secrets input via the touch screen. [5] explores the feasibility of such attacks finding in one experiment the lock screen pattern was partially identifiable 92% of the time and full identifiable 68% of the time.

These vulnerabilities have led to the development of lock screens which use a user biometric in an attempt to increase security. Facial recognition and finger print scanners have been employed as lock screen mechanisms. These methods

insufficient to protect the device from attack. [6] demonstrates a method to exploit the finger print scanner on an android device using printed fingerprints. This method is simple and fast as long as a print of the authentic user's finger can be obtained. Other works by Germany's Chaos Computer Club [7] have show that it is possible to lift a finger print belonging to the authentic user from the device touch screen and use it to pass the finger print scanner authentication on Apple's Iphone $4S$ and 5. Attacks against facial recognition schemes involve spoofing the facial features of the authentic user in order to pass facial recognition authentication. [8] accesses the practically anti-spoofing measures in real word scenarios observing low generalization of and possible database bias in existing schemes.

In many situations, an attacker may not even need to pass the lock screen authentication. Imagine a situation where the authentic user of a device preforms the authentication, unlocking the device. The device then falls into the hands of an attacker. This attacker can not only exploit the authenticated state of the device, but may use the authenticated state to disable the lock screen entirely; Thus allowing permanent access to all applications on the device. [9] surveyed the lock screen behavior of 320 individuals ages $18-67$ with a median age of 31. Of these individuals, 39.6% rated themselves as having a very high level of IT expertise. The results of this survey indicate 56.3% of the participants did not use a lock screen at all.

This paper does not propose a new method of authenticating the user through the lock screen. Instead we seek to mitigate risk of loss should a device become compromised. We describe a continuous authentication layer which can distinguish among users using a biometric of the user generated though data entry on an Android device's soft keyboard. In many situations there exists a trade off between security and convenience from the user's perspective. This trade off can be observed in the Android lock screen. The necessity to enter a pin, password, or pattern every time access to the device is desired is an inconvenience. In exchange for this inconvenience, users are rewarded with some security. The solution presented in this paper provides additional security while requiring no additional actions from the user. This is accomplished by recording a biometric of the user's interactions with the touch screen in the background. The user continues, unaffected by this collection, interacting with the device as they normally would. The most resent interactions are then tested against previous actions to determine if the user's pattern has begun to deviate. Deviations may indicate that a malicious party has gain control over the device.

We provide a step forward, in mobile device security by establishing a continuous, unobtrusive user identity. This identity enhances the ability of mobile devices to recognize when the device may have come under the physical possession of an illegitimate user. This system provides innovations in the following areas:

- We show that touch screen interactions may be used in order to distinguish a legitimate user of a mobile device apart from illegitimate users. Specifically, section 3 shows how a combination of a touch screen pressure and the location on the screen may be used to develop a model of that user's behavior.

- We establish the behavior of a user on a device is unique to the user. Many applications, such as Google Wallet, can benefit from an increased assurance the user is authentic. Section 4 establishes that a difference in user identity may be detected by our implementation.

- We establish the behavior of a user on a device is unique to the device. Such an identity could be useful in defeating attacks where a user is tricked into entering secret data, such as a password, on another device. Section 4 establishes that a difference in device identity may be detected by our implementation.

- The system is unobtrusive meaning there is no convenience cost assessed upon the user. All security improvements are accomplished without requiring any additional actions from the user. Our implementation, capable of utilizing touch screen data collected in the background, is described in Section 3

- The performance of this system has sufficiently high accuracy, $(70-90+\%)$, and low computational overhead, $(1-5sec)$, to make it practical. A performance comparison is presented in Section 4 which demonstrates the computation time as a function of the number of touch screen interactions used and the running time of the system on a Nexus 7 tablet.

- This work solves the problem of detecting a non-authentic user in cases where the lock screen has been bypassed. Other solutions fail to consider this problem or fail to provide a sufficient solution as discussed in Section 2.

In deciding if a user is legitimate, it is useful to define three categories: something the user knows, something the user has, and something the user is. Traditional mobile authentication schemes, such as a lock screen, utilize only something a user knows. Interactions between a user and the touchscreen of a mobile device are rich with information. Current solutions suffer from underutilization of this information; they discard much of the content of these interactions in favor using the location of the interactions exclusively. Our system utilizes pressure, time, and location capturing the currently under-utilized potential of these interactions to expose patterns unique to a user.

We use these properties to construct a model of how the user interacts with a mobile device. This model takes as input a sequence of touches preformed by the user. From this sequence probabilities are developed which represent the likelihood of a given touch screen interaction based on the properties of a number of previous interactions. We use an $n-gram$ Markov model, a subclass of Markov text analysis. This model uses n previous states in computing next state probabilities. This model is explained more throughly in Section 3.

2. THE PROBLEM
3. THE SOLUTION
The main idea of this paper is that user touch screen interactions may be used in order to distinguish a legitimate

user of a mobile device apart from illegitimate users. We implement a continuous authentication system based on user interactions with the soft keyboard of a mobile device. This system uses properties of the interactions including pressure and location.

A large part of a user's interactions with a mobile device involve the input of data with a soft keyboard. These soft keyboard applications require that the user put their finger on the screen at a consistent location to indicate a given letter should be taken as input. This input is rich with information including pressure, key code, and timestamp. As the keys on the soft keyboard are always in the same place on the screen, we take the key code value to represent the location in our model. Through interactions with multiple applications over time, the user produces a sequence of these inputs. This sequence is used to construct a model of user behavior.

The goal in creating the model is to be able to distinguish the behavior of one user from another user on the same device and from the same user on a different device. That is, the pairing of user and device will create a model unique to that pair. If either the user or device is changed, the model will be sufficiently different that it is detectable. The input sequence will be used to characterize the user-device pair. This uniqueness is possible because the pressure metric is a product of unique properties in the silicon of the device and the finger of the human user. Pressure is processed though the capacitive touch and sensor circuitry. The silicon's unique properties are a product of the fabrication process reflected when pressure is measured. The uniqueness of the human user is derived from the way in which they touch the screen.

Let's say we want to model the behavior of an individual in terms of where they choose to spend their time. Say further that the goal in creating this model is to predict their $t+1^{st}$ location based on their current location. The outcome of using a Markov model to describe a system is a vector $\hat{P}$ of probabilities for each possible state. For the individual in our behavior model, $\hat{P}_i$ corresponds to the probability that the i_{th} location will be the location of the person at time $t+1$ if the current time is t. Such a probability outcome for our individual might be that if at time t the person is in the living room, then at time $t+1$ there might be a 70% probability they are still in the living room, a 20% probability they are in the kitchen, and a 10% probability they are in the bathroom. Such a model might be useful in understanding the behavior patterns of one person, or comparing behavior patterns among persons.

Continuing the example of predicting the next location of a person, we stated the outcome of the model as a vector giving probabilities for each state. The full Markov model uses the sequence of all previous states in computing the probability of the next state. This approach is grounded in maximal likelihood estimation(MLE). MLE is formulated as follows. Each probability depends on all previous states of the system according to :::

In the full Markov model, the probabilities for the state at time $t+1$ are determined by the state at time values 0 to t. In our implementation we use an n-gram Markov model

which uses the previous n states to compute the next state probability. This n is referred to as the window size while the n states are referred to as a window. The window precedes a single state. The location of the person in the previous example might be predicted by the previous three rooms they located themselves within. In other words, location $t+1$ might be predicted states $t-2$, $t-1$, and t This approach develops a close approximation to the full Markov model while forgoing the complexity of computation associated with MLE. The result is an advantage in speed of computation.

The probability computation takes a sequence of previous states as input. Determining the probability for transitioning to another state given the current state can be done with the following algorithm.

1. compute the number of occurrences L for each window W

2. for all windows, for each token, compute $\frac{V_i}{L_i}$ where

   - V_i = number of token i which succeed window W_i
   - L_i = total number of occurrences of window W_i

This computation is of less complexity than the probability computation for the full Markov model. In addition, there are only two quantities which need to be tracked. First it is necessary to know the total number of occurrences for a given window. Second the number of times a touch succeeds a window must be known.

Our implementation utilizes an n-gram model. Similar to the earlier example of predicting locations, our goal is to predict a user's behavior in interacting with a soft keyboard. Locations are analogous to keys, but an interaction with a key on the soft keyboard is more complex than existing in a room. Existence, in this case, is a binary decision. A person is either in a room or not in a room. Comparatively, touch interactions with keys have many degrees of complexity. A mobile device user is not simply touching a key or not touching a key, they are doing so by applying an amount of pressure to the screen within the area enclosed by the key. In this implementation we do not consider the variance in finger placement within a key, but we do capture pressure variations within a key. A state or token within the model is determined by the key pressed in combination with the pressure with which it was pressed. Under this methodology, all of the following would be considered different: "a" with pressure .5, "a" with pressure .8, and "b" with pressure .5. The first two illustrate a same key, different pressure scenario while the first and last describe a situation with different key, same pressure. In both cases our model takes these to be different states.

Our n-gram Markov model uses tokens which are a tuple of location and pressure generated through user touch screen interactions. There are a very large number of possible location, pressure combinations. Since it is unlikely that the user will be very precise in location or pressure, having such a large number of tokens creates a situation where each sequence of touch interactions will be different for the same

user on the same device; this is not desirable. In fact, if the entire space were used the variations in location and pressure, even when generated by a single user, would result in a very large number of tokens each having low probabilities of succeeding any n token sequence.

We require some way of grouping numbers of elements this space to make the sequences the user's generate reproducible. Grouping here involves the selection of a range of values which will be considered the same. For instance, if there are apples of varying sizes which need to be categorized as "small", "medium" or "large", then we need to choose a range of values from some metric which could be used to describe all apples. Perhaps weight is chosen as this metric. The "small" grouping of apples might include apples which are less than 1.0 pound. In choosing how to group elements care must be taken not to group too many pressures and locations together; doing so would fail to capture characteristics of the sequence unique to a user. Thus multiple users would present with similar sequences making it difficult to distinguish among users.

In our implementation, we choose to use the key code produced by a touch interaction as a representation for the location of the event. Given that users use a soft keyboard to input textual data, it stands to reason that interactions which produce the same key code have equivalent user intent. A different approach is used in determining what pressure values are to be grouped together. The two extremes for grouping the pressure metric are to consider all pressure values to be the same token on the one hand. In effect, this does not use pressure at all. Alternatively all possible pressure values reported by the device could be used. The former masks any potential pressure variation unique to a user while the later would capture the variation of a user at two fine a granularity. Neither scheme is are desirable as a whole, but both have desirable properties. Using all possible pressure values captures as much uniqueness as possible. This uniqueness would help to distinguish between users. However patters created using this scheme would fail to be reproducible by the same user. Contrast this with grouping all pressure values together. This scheme produces patters which are entirely reproducible, but fails to be able to distinguish between users. The goal is to maximize the degree to which users may be differentiated while maintaining reproducibility for the same user.

In our implementation, groupings for pressure values are selected based on the user's behavior. Pressure ranges are chosen around values which the user frequents. The goal of choosing tokens in this way is to capture as much variation as possible. Consider an alternative scheme where ranges are uniform across all possible pressure values. It is feasible that the user uses a fairly consistent pressure when preforming all actions. Under uniform ranges this type of behavior might capture no variation; there is the potential for all pressure values to fall within one range. This is not desirable as only the magnitude of the pressure is captured. All of the potential variability contained in the pressure metric is lost. An alternative method of constructing the pressure ranges which does capture this variability is as follows.

1. Find the mean μ and standard deviation σ for all touch

interactions' pressure values

2. Divide the range $[\mu - 2\sigma, \mu + 2\sigma]$ into k pressure ranges

k is then the number tokens created for each location. The total number of tokens is k multiplied by the number of locations. 2 sigma is chosen because 95% of the user's pressure values will fall within this range. This will throw away some touch interactions which have very high or very low pressures relative to the user's average. The benefit in doing this is that the pressure are then constructed around area where the user's variability is more likely to be expressed.

Windows within our n-gram Markov model are then a sequence of length n touch events. These sequences may overlap. To illustrate this suppose $n = 2$ and the user has input "apple". Each character has an associated pressure value, but suppose the number of tokens per location is 1. The effect of this will be that all equivalent characters, such as two "p" characters, will be considered to be the same token within the model. The windows for this sequence of characters will be ["ap", "pp", "pl", "le"].

Let us return to the situation where a Markov model was used to predict the $t + 1^{st}$ location of an individual. Now suppose that these probabilities have been developed for two people, A and B, who's behavior patterns we would like to compare. Our goal is to quantify the difference between the location patterns of these individuals. Suppose that in both cases there are three rooms, living room, kitchen, and bathroom, and that the locations of A and B are measured at 4 time instants. A is in the living room during the first time instant. In subsequent time instants, A is in the kitchen then living room then bathroom. The result of these movements is the probabilities 0%, 50%, 50%. These probabilities describe A's how likely A is to be in the living room, kitchen, and bathroom at the next time instant, $t + 1$, if A is currently in the living room. B, on the other hand, at the measured time points is located in the living room then living room then kitchen then bathroom. In this case the result is probabilities 50%, 50%, 0% that B will be in the living room, kitchen, and bathroom at the next time instant if B is currently in the living room.

Now suppose the goal is to compare the movement of A and B from the living room. The end result should be some number which represents the difference in probabilities between A and B. Our approach consists of computing the average absolute difference between the probabilities. In the scenario described above the average difference between A and B is computed by $\frac{|0\% - 50\%| + |50\% - 50\%| + |50\% - 0\%|}{3}$. The resulting value, 0.33, is a floating point value between 0.0 and 1.0 which represents the closeness of the two vectors. 0 indicates maximal closeness while 1 describes two vectors which are a different as possible.

In our implementation the difference between two models is computed with a method analogous to the comparison of movement between A an B. Comparing models of user input is further complicated by the existence of multiple windows. Comparatively, the previous example described how to compute the average difference for a single window. The following algorithm outlines the computations completed to

compute probabilities in our system. Suppose there are two lists of touch interactions which need to be compared. List U contains the authentic user's behavior while list O contains other touches of unknown origin. The goal is to classify this list O as coming from the same user an device as U or not coming from the same user and device as U.

1. Compute the distribution (μ, σ) values for the the list U

2. Set the set the distribution of list O equal to that computed for U

3. For both lists, compute a set T of k tokens in the range $[\mu - 2\sigma, \mu + 2\sigma]$

4. For both lists, compute a set W of all windows

   - for each element in W, determine the number of occurrences
   - for each element in W, determine the successor touches
   - let W^U represent the windows in U and W^O represent the windows in O

5. Determine the probabilities associated with a token succeeding a window as $P(T_i|W_j) = \frac{succeeds(T_i, W_j)}{occurrences(W_j)}$ where

   - T_i represents a token i from set T
   - $P(T_i|W)$ represents the probability of token T_i given that W_j precedes T_i
   - $occurrences(W_j)$ represents the number of occurrences of W_j in W
   - $succeeds(T_i, W_j)$ computes the number of times T_i succeeds W_j

6. For each W^O, compute the difference between the corresponding W^U.

   - The difference between windows is defined as the average difference between the successor touch probabilities

7. The difference between the models is then $\Sigma_i^n \frac{|W_i^U - W_i^O|}{||W^O||}$ where

   - n is the number of windows
   - W_i^U is the window in W^U which corresponds to and equivalent window W_i^O in W^O
   - $-$ represents the window difference operation described above
   - $||W^O||$ is the number of windows in O

There are several points from the above approach which require mention. The same distribution is used for both models. This is to ensure the tokens used when comparing models are the same. In computing windows, the previously computed set of tokens is used. If there is no window in W corresponding to a window in O, then the windows are considered to be maximally different from one another. In other words, having a window in list O which does not exist in list
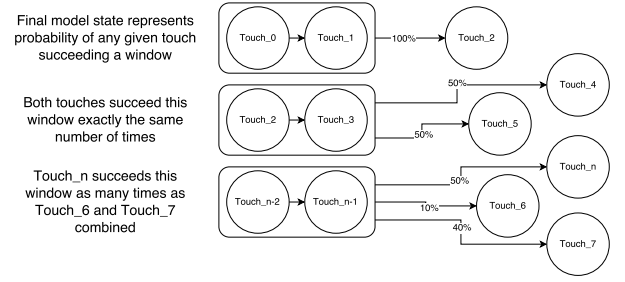

Figure 1: Example 2-Markov model after the probabilities have been calculated. The rounded rectangles indicate a sequence of touch interactions which precede the following touch interaction with some probability p. p for token T after sequence W is computed as occurrences of T after W by occurrences of W.

U is penalized by considering the the difference between the windows to be 1.0.

Such a system might be incorporated into the Android environment in the following way. A background service could be used to collect MotionEvent objects from soft keyboard applications. This would allow touch interactions to be collected over time. A model of these touch events could then be constructed in the background. Periodic authentications could compare new touch interactions against existing older touches which have come from the user. The number of touches used in the authentication could be adjusted over time. This would allow for lower accuracy models to be constructed with relatively few touches while higher accuracies would be achievable as the system collects more touch interaction data. The effect would be a small amount of added security initially which improves over time. Many things could be done if the result of this authentication find the user is illegitimate. One approach might be to lock the phone, forcing the user to re-authenticate with some other method.

The following section provides evidence this scheme works. Support that this scheme is capable of using touch screen interactions to distinguish from among unique pairs of users and devices is provided.

4. THE DETAILS

In order to answer the question of whether or not touch screen interactions may be used in order to distinguish between users a system is implemented to gather and analyze data from interactions with the touchscreen of an Android device. This data consists of location, pressure, and time values associated with user's interactions with a soft keyboard. For gathering purposes, a keyboard application was modified to record the necessary data values. Two users were enlisted to acquire a large amount of data on two different Nexus 7 tablets. In effect this creates four user, device combinations. In order to analyze the collected data, the system described in 3 has been constructed.
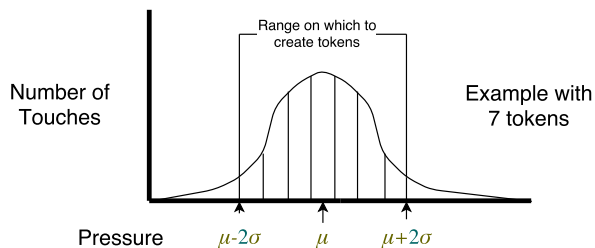
The data were analyzed by

Figure 2: **Tokens are only created for pressure range** $\mu \pm 2\sigma$ **for each key. Touches with pressure values** $p > \mu + 2\sigma$ **and** $p < \mu - 2\sigma$ **are thrown out. This eliminates outliers creating increased reproducibility.**
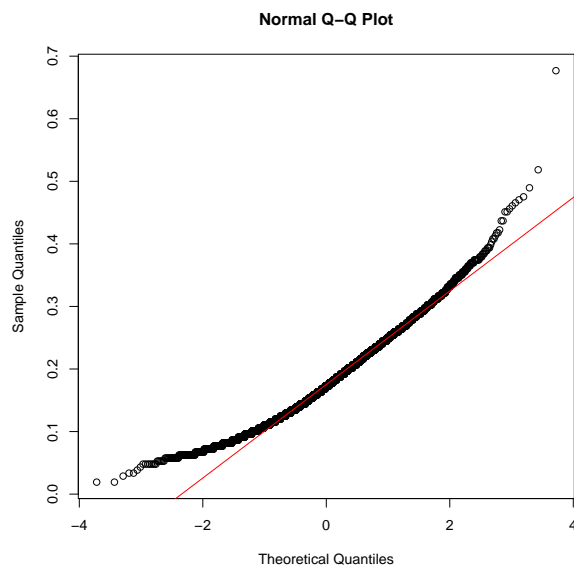

Figure 4: **This Q-Q Plot describes data from a data set having a right skew compared to normally distributed data.**
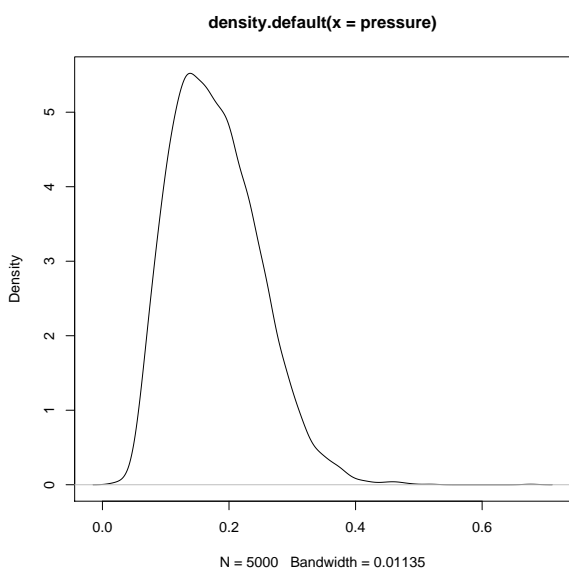

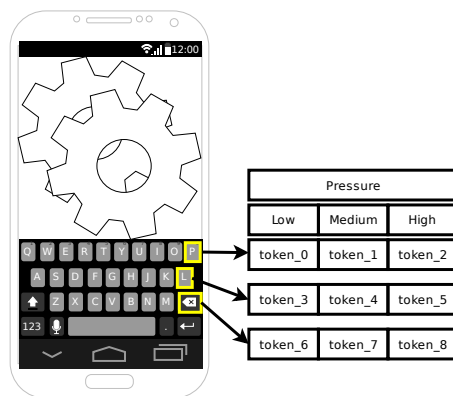Figure 3: **Density of touchscreen interactions' pressure values for one user.**

Figure 5: **Multiple tokens,** $k = 3$ **above, correspond to each key location. A touch screen interaction is assigned a token based on key location and pressure.**
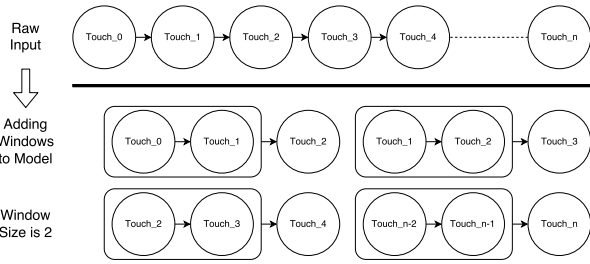
Figure 6: The top of this figure depicts the raw touchscreen interaction sequence. Each touch represents a single interaction between the human user and the soft keyboard. The diagram's lower portion demonstrates how the raw input is parsed into a 2-Markov model. The bottom left image can be interpreted to say that Touch_4 succeeds the sequence Touch_2, Touch_3 with some probability p.
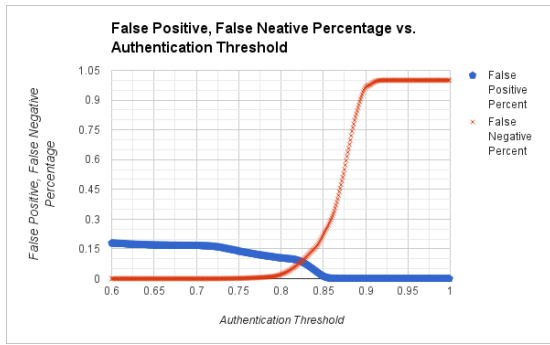

Figure 7: False positive and false negative percentages vary as the authentication threshold is adjusted.

5. USER-DEVICE PAIR DISCRIMINATION

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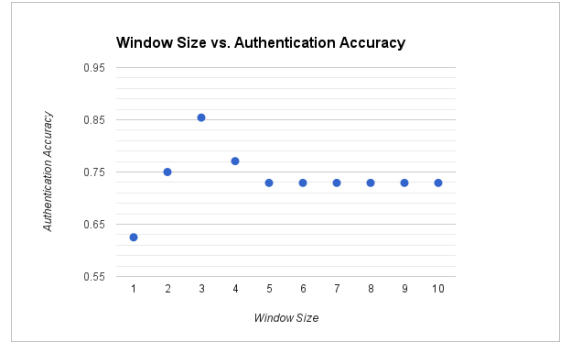

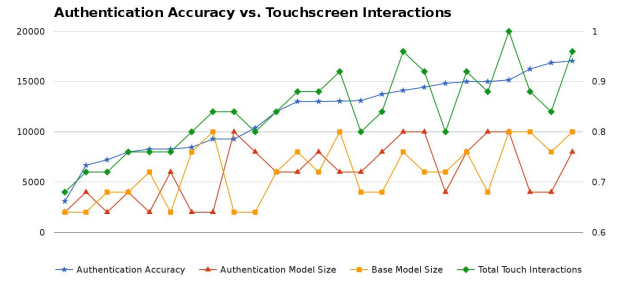**Figure 8: The effect of n in n-Markov Model window size on authentication accuracy.**

Figure 9: The left y axis describes the size of model in number of touchscreen interactions. We compare authentication accuracy(blue star), measured on the right y axis, to authentication model size(red triangle), base model size(yellow square), and total touch interactions(green diamond) measured on the left y axis. Total touch interactions is the sum of base model size and authentication model size.
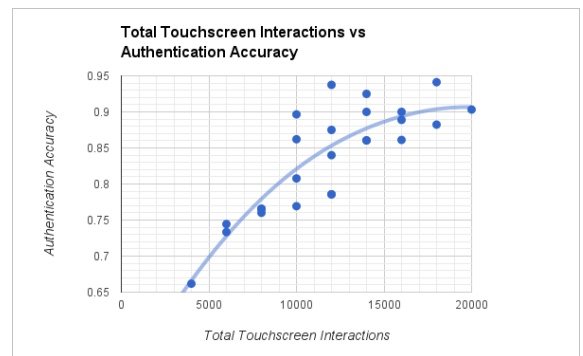

Figure 10: Authentication accuracy can be seen as a function of the total number of touch screen interactions used in model construction. Total touch interactions is the sum of base model size and authentication model size.
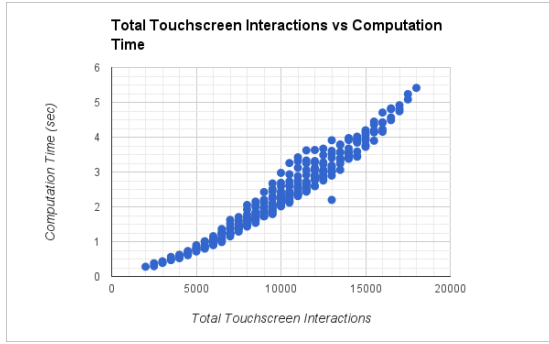
Figure 11: The computation time, measured in seconds(sec), on a Nexus 7 tablet is a function of $TotalSize = base\_model\_size + auth\_model\_size$. Model sizes are measured by number of touch interactions used in their construction.

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Nulla malesuada porttitor diam. Donec felis erat, congue non, volutpat at, tincidunt tristique, libero. Vivamus viverra fermentum felis. Donec nonummy pellentesque ante. Phasellus adipiscing semper elit. Proin fermentum massa ac quam. Sed diam turpis, molestie vitae, placerat a, molestie nec, leo. Maecenas lacinia. Nam ipsum ligula, eleifend at, accumsan nec, suscipit a, ipsum. Morbi blandit ligula feugiat magna. Nunc eleifend consequat lorem. Sed lacinia nulla vitae enim. Pellentesque tincidunt purus vel magna. Integer non enim. Praesent euismod nunc eu purus. Donec bibendum quam in tellus. Nullam cursus pulvinar lectus. Donec et mi. Nam vulputate metus eu enim. Vestibulum pellentesque felis eu massa.

Quisque ullamcorper placerat ipsum. Cras nibh. Morbi vel justo vitae lacus tincidunt ultrices. Lorem ipsum dolor sit amet, consectetuer adipiscing elit. In hac habitasse platea dictumst. Integer tempus convallis augue. Etiam facilisis. Nunc elementum fermentum wisi. Aenean placerat. Ut imperdiet, enim sed gravida sollicitudin, felis odio placerat quam, ac pulvinar elit purus eget enim. Nunc vitae tortor. Proin tempus nibh sit amet nisl. Vivamus quis tortor vitae risus porta vehicula.

Fusce mauris. Vestibulum luctus nibh at lectus. Sed bibendum, nulla a faucibus semper, leo velit ultricies tellus, ac venenatis arcu wisi vel nisl. Vestibulum diam. Aliquam pellentesque, augue quis sagittis posuere, turpis lacus congue quam, in hendrerit risus eros eget felis. Maecenas eget erat in sapien mattis porttitor. Vestibulum porttitor. Nulla facilisi. Sed a turpis eu lacus commodo facilisis. Morbi fringilla, wisi in dignissim interdum, justo lectus sagittis dui, et ve-

hicula libero dui cursus dui. Mauris tempor ligula sed lacus. Duis cursus enim ut augue. Cras ac magna. Cras nulla. Nulla egestas. Curabitur a leo. Quisque egestas wisi eget nunc. Nam feugiat lacus vel est. Curabitur consectetuer.

Suspendisse vel felis. Ut lorem lorem, interdum eu, tincidunt sit amet, laoreet vitae, arcu. Aenean faucibus pede eu ante. Praesent enim elit, rutrum at, molestie non, nonummy vel, nisl. Ut lectus eros, malesuada sit amet, fermentum eu, sodales cursus, magna. Donec eu purus. Quisque vehicula, urna sed ultricies auctor, pede lorem egestas dui, et convallis elit erat sed nulla. Donec luctus. Curabitur et nunc. Aliquam dolor odio, commodo pretium, ultricies non, pharetra in, velit. Integer arcu est, nonummy in, fermentum faucibus, egestas vel, odio.

Sed commodo posuere pede. Mauris ut est. Ut quis purus. Sed ac odio. Sed vehicula hendrerit sem. Duis non odio. Morbi ut dui. Sed accumsan risus eget odio. In hac habitasse platea dictumst. Pellentesque non elit. Fusce sed justo eu urna porta tincidunt. Mauris felis odio, sollicitudin sed, volutpat a, ornare ac, erat. Morbi quis dolor. Donec pellentesque, erat ac sagittis semper, nunc dui lobortis purus, quis congue purus metus ultricies tellus. Proin et quam. Class aptent taciti sociosqu ad litora torquent per conubia nostra, per inceptos hymenaeos. Praesent sapien turpis, fermentum vel, eleifend faucibus, vehicula eu, lacus.

Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Donec odio elit, dictum in, hendrerit sit amet, egestas sed, leo. Praesent feugiat sapien aliquet odio. Integer vitae justo. Aliquam vestibulum fringilla lorem. Sed neque lectus, consectetuer at, consectetuer sed, eleifend ac, lectus. Nulla facilisi. Pellentesque eget lectus. Proin eu metus. Sed porttitor. In hac habitasse platea dictumst. Suspendisse eu lectus. Ut mi mi, lacinia sit amet, placerat et, mollis vitae, dui. Sed ante tellus, tristique ut, iaculis eu, malesuada ac, dui. Mauris nibh leo, facilisis non, adipiscing quis, ultrices a, dui.

Morbi luctus, wisi viverra faucibus pretium, nibh est placerat odio, nec commodo wisi enim eget quam. Quisque libero justo, consectetuer a, feugiat vitae, porttitor eu, libero. Suspendisse sed mauris vitae elit sollicitudin malesuada. Maecenas ultricies eros sit amet ante. Ut venenatis velit. Maecenas sed mi eget dui varius euismod. Phasellus aliquet volutpat odio. Vestibulum ante ipsum primis in faucibus orci luctus et ultrices posuere cubilia Curae; Pellentesque sit amet pede ac sem eleifend consectetuer. Nullam elementum, urna vel imperdiet sodales, elit ipsum pharetra ligula, ac pretium ante justo a nulla. Curabitur tristique arcu eu metus. Vestibulum lectus. Proin mauris. Proin eu nunc eu urna hendrerit faucibus. Aliquam auctor, pede consequat laoreet varius, eros tellus scelerisque quam, pellentesque hendrerit ipsum dolor sed augue. Nulla nec lacus.

Suspendisse vitae elit. Aliquam arcu neque, ornare in, ullamcorper quis, commodo eu, libero. Fusce sagittis erat at erat tristique mollis. Maecenas sapien libero, molestie et, lobortis in, sodales eget, dui. Morbi ultrices rutrum lorem. Nam elementum ullamcorper leo. Morbi dui. Aliquam sagittis. Nunc placerat. Pellentesque tristique sodales est. Maecenas imperdiet lacinia velit. Cras non urna. Morbi eros

pede, suscipit ac, varius vel, egestas non, eros. Praesent malesuada, diam id pretium elementum, eros sem dictum tortor, vel consectetuer odio sem sed wisi.

Sed feugiat. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Ut pellentesque augue sed urna. Vestibulum diam eros, fringilla et, consectetuer eu, nonummy id, sapien. Nullam at lectus. In sagittis ultrices mauris. Curabitur malesuada erat sit amet massa. Fusce blandit. Aliquam erat volutpat. Aliquam euismod. Aenean vel lectus. Nunc imperdiet justo nec dolor.

Etiam euismod. Fusce facilisis lacinia dui. Suspendisse potenti. In mi erat, cursus id, nonummy sed, ullamcorper eget, sapien. Praesent pretium, magna in eleifend egestas, pede pede pretium lorem, quis consectetuer tortor sapien facilisis magna. Mauris quis magna varius nulla scelerisque imperdiet. Aliquam non quam. Aliquam porttitor quam a lacus. Praesent vel arcu ut tortor cursus volutpat. In vitae pede quis diam bibendum placerat. Fusce elementum convallis neque. Sed dolor orci, scelerisque ac, dapibus nec, ultricies ut, mi. Duis nec dui quis leo sagittis commodo.

Aliquam lectus. Vivamus leo. Quisque ornare tellus ullamcorper nulla. Mauris porttitor pharetra tortor. Sed fringilla justo sed mauris. Mauris tellus. Sed non leo. Nullam elementum, magna in cursus sodales, augue est scelerisque sapien, venenatis congue nulla arcu et pede. Ut suscipit enim vel sapien. Donec congue. Maecenas urna mi, suscipit in, placerat ut, vestibulum ut, massa. Fusce ultrices nulla et nisl.

Etiam ac leo a risus tristique nonummy. Donec dignissim tincidunt nulla. Vestibulum rhoncus molestie odio. Sed lobortis, justo et pretium lobortis, mauris turpis condimentum augue, nec ultricies nibh arcu pretium enim. Nunc purus neque, placerat id, imperdiet sed, pellentesque nec, nisl. Vestibulum imperdiet neque non sem accumsan laoreet. In hac habitasse platea dictumst. Etiam condimentum facilisis libero. Suspendisse in elit quis nisl aliquam dapibus. Pellentesque auctor sapien. Sed egestas sapien nec lectus. Pellentesque vel dui vel neque bibendum viverra. Aliquam porttitor nisl nec pede. Proin mattis libero vel turpis. Donec rutrum mauris et libero. Proin euismod porta felis. Nam lobortis, metus quis elementum commodo, nunc lectus elementum mauris, eget vulputate ligula tellus eu neque. Vivamus eu dolor.

Nulla in ipsum. Praesent eros nulla, congue vitae, euismod ut, commodo a, wisi. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Aenean nonummy magna non leo. Sed felis erat, ullamcorper in, dictum non, ultricies ut, lectus. Proin vel arcu a odio lobortis euismod. Vestibulum ante ipsum primis in faucibus orci luctus et ultrices posuere cubilia Curae; Proin ut est. Aliquam odio. Pellentesque massa turpis, cursus eu, euismod nec, tempor congue, nulla. Duis viverra gravida mauris. Cras tincidunt. Curabitur eros ligula, varius ut, pulvinar in, cursus faucibus, augue.

Nulla mattis luctus nulla. Duis commodo velit at leo. Aliquam vulputate magna et leo. Nam vestibulum ullamcorper leo. Vestibulum condimentum rutrum mauris. Donec id

mauris. Morbi molestie justo et pede. Vivamus eget turpis sed nisl cursus tempor. Curabitur mollis sapien condimentum nunc. In wisi nisl, malesuada at, dignissim sit amet, lobortis in, odio. Aenean consequat arcu a ante. Pellentesque porta elit sit amet orci. Etiam at turpis nec elit ultricies imperdiet. Nulla facilisi. In hac habitasse platea dictumst. Suspendisse viverra aliquam risus. Nullam pede justo, molestie nonummy, scelerisque eu, facilisis vel, arcu.

Curabitur tellus magna, porttitor a, commodo a, commodo in, tortor. Donec interdum. Praesent scelerisque. Maecenas posuere sodales odio. Vivamus metus lacus, varius quis, imperdiet quis, rhoncus a, turpis. Etiam ligula arcu, elementum a, venenatis quis, sollicitudin sed, metus. Donec nunc pede, tincidunt in, venenatis vitae, faucibus vel, nibh. Pellentesque wisi. Nullam malesuada. Morbi ut tellus ut pede tincidunt porta. Lorem ipsum dolor sit amet, consectetuer adipiscing elit. Etiam congue neque id dolor.

Donec et nisl at wisi luctus bibendum. Nam interdum tellus ac libero. Sed sem justo, laoreet vitae, fringilla at, adipiscing ut, nibh. Maecenas non sem quis tortor eleifend fermentum. Etiam id tortor ac mauris porta vulputate. Integer porta neque vitae massa. Maecenas tempus libero a libero posuere dictum. Vestibulum ante ipsum primis in faucibus orci luctus et ultrices posuere cubilia Curae; Aenean quis mauris sed elit commodo placerat. Class aptent taciti sociosqu ad litora torquent per conubia nostra, per inceptos hymenaeos. Vivamus rhoncus tincidunt libero. Etiam elementum pretium justo. Vivamus est. Morbi a tellus eget pede tristique commodo. Nulla nisl. Vestibulum sed nisl eu sapien cursus rutrum.

Nulla non mauris vitae wisi posuere convallis. Sed eu nulla nec eros scelerisque pharetra. Nullam varius. Etiam dignissim elementum metus. Vestibulum faucibus, metus sit amet mattis rhoncus, sapien dui laoreet odio, nec ultricies nibh augue a enim. Fusce in ligula. Quisque at magna et nulla commodo consequat. Proin accumsan imperdiet sem. Nunc porta. Donec feugiat mi at justo. Phasellus facilisis ipsum quis ante. In ac elit eget ipsum pharetra faucibus. Maecenas viverra nulla in massa.

Nulla ac nisl. Nullam urna nulla, ullamcorper in, interdum sit amet, gravida ut, risus. Aenean ac enim. In luctus. Phasellus eu quam vitae turpis viverra pellentesque. Duis feugiat felis ut enim. Phasellus pharetra, sem id porttitor sodales, magna nunc aliquet nibh, nec blandit nisl mauris at pede. Suspendisse risus risus, lobortis eget, semper at, imperdiet sit amet, quam. Quisque scelerisque dapibus nibh. Nam enim. Lorem ipsum dolor sit amet, consectetuer adipiscing elit. Nunc ut metus. Ut metus justo, auctor at, ultrices eu, sagittis ut, purus. Aliquam aliquam.

Etiam pede massa, dapibus vitae, rhoncus in, placerat posuere, odio. Vestibulum luctus commodo lacus. Morbi lacus dui, tempor sed, euismod eget, condimentum at, tortor. Phasellus aliquet odio ac lacus tempor faucibus. Praesent sed sem. Praesent iaculis. Cras rhoncus tellus sed justo ullamcorper sagittis. Donec quis orci. Sed ut tortor quis tellus euismod tincidunt. Suspendisse congue nisl eu elit. Aliquam tortor diam, tempus id, tristique eget, sodales vel, nulla. Praesent tellus mi, condimentum sed, viverra at, con-

sectetuer quis, lectus. In auctor vehicula orci. Sed pede sapien, euismod in, suscipit in, pharetra placerat, metus. Vivamus commodo dui non odio. Donec et felis.

Etiam suscipit aliquam arcu. Aliquam sit amet est ac purus bibendum congue. Sed in eros. Morbi non orci. Pellentesque mattis lacinia elit. Fusce molestie velit in ligula. Nullam et orci vitae nibh vulputate auctor. Aliquam eget purus. Nulla auctor wisi sed ipsum. Morbi porttitor tellus ac enim. Fusce ornare. Proin ipsum enim, tincidunt in, ornare venenatis, molestie a, augue. Donec vel pede in lacus sagittis porta. Sed hendrerit ipsum quis nisl. Suspendisse quis massa ac nibh pretium cursus. Sed sodales. Nam eu neque quis pede dignissim ornare. Maecenas eu purus ac urna tincidunt congue.

Donec et nisl id sapien blandit mattis. Aenean dictum odio sit amet risus. Morbi purus. Nulla a est sit amet purus venenatis iaculis. Vivamus viverra purus vel magna. Donec in justo sed odio malesuada dapibus. Nunc ultrices aliquam nunc. Vivamus facilisis pellentesque velit. Nulla nunc velit, vulputate dapibus, vulputate id, mattis ac, justo. Nam mattis elit dapibus purus. Quisque enim risus, congue non, elementum ut, mattis quis, sem. Quisque elit.

Maecenas non massa. Vestibulum pharetra nulla at lorem. Duis quis quam id lacus dapibus interdum. Nulla lorem. Donec ut ante quis dolor bibendum condimentum. Etiam egestas tortor vitae lacus. Praesent cursus. Mauris bibendum pede at elit. Morbi et felis a lectus interdum facilisis. Sed suscipit gravida turpis. Nulla at lectus. Vestibulum ante ipsum primis in faucibus orci luctus et ultrices posuere cubilia Curae; Praesent nonummy luctus nibh. Proin turpis nunc, congue eu, egestas ut, fringilla at, tellus. In hac habitasse platea dictumst.

Vivamus eu tellus sed tellus consequat suscipit. Nam orci orci, malesuada id, gravida nec, ultricies vitae, erat. Donec risus turpis, luctus sit amet, interdum quis, porta sed, ipsum. Suspendisse condimentum, tortor at egestas posuere, neque metus tempor orci, et tincidunt urna nunc a purus. Sed facilisis blandit tellus. Nunc risus sem, suscipit nec, eleifend quis, cursus quis, libero. Curabitur et dolor. Sed vitae sem. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Maecenas ante. Duis ullamcorper enim. Donec tristique enim eu leo. Nullam molestie elit eu dolor. Nullam bibendum, turpis vitae tristique gravida, quam sapien tempor lectus, quis pretium tellus purus ac quam. Nulla facilisi.

Duis aliquet dui in est. Donec eget est. Nunc lectus odio, varius at, fermentum in, accumsan non, enim. Aliquam erat volutpat. Proin sit amet nulla ut eros consectetuer cursus. Phasellus dapibus aliquam justo. Nunc laoreet. Donec consequat placerat magna. Duis pretium tincidunt justo. Sed sollicitudin vestibulum quam. Nam quis ligula. Vivamus at metus. Etiam imperdiet imperdiet pede. Aenean turpis. Fusce augue velit, scelerisque sollicitudin, dictum vitae, tempor et, pede. Donec wisi sapien, feugiat in, fermentum ut, sollicitudin adipiscing, metus.

Donec vel nibh ut felis consectetuer laoreet. Donec pede. Sed id quam id wisi laoreet suscipit. Nulla lectus dolor,

aliquam ac, fringilla eget, mollis ut, orci. In pellentesque justo in ligula. Maecenas turpis. Donec eleifend leo at felis tincidunt consequat. Aenean turpis metus, malesuada sed, condimentum sit amet, auctor a, wisi. Pellentesque sapien elit, bibendum ac, posuere et, congue eu, felis. Vestibulum mattis libero quis metus scelerisque ultrices. Sed purus.

Donec molestie, magna ut luctus ultrices, tellus arcu nonummy velit, sit amet pulvinar elit justo et mauris. In pede. Maecenas euismod elit eu erat. Aliquam augue wisi, facilisis congue, suscipit in, adipiscing et, ante. In justo. Cras lobortis neque ac ipsum. Nunc fermentum massa at ante. Donec orci tortor, egestas sit amet, ultrices eget, venenatis eget, mi. Maecenas vehicula leo semper est. Mauris vel metus. Aliquam erat volutpat. In rhoncus sapien ac tellus. Pellentesque ligula.

Cras dapibus, augue quis scelerisque ultricies, felis dolor placerat sem, id porta velit odio eu elit. Aenean interdum nibh sed wisi. Praesent sollicitudin vulputate dui. Praesent iaculis viverra augue. Quisque in libero. Aenean gravida lorem vitae sem ullamcorper cursus. Nunc adipiscing rutrum ante. Nunc ipsum massa, faucibus sit amet, viverra vel, elementum semper, orci. Cras eros sem, vulputate et, tincidunt id, ultrices eget, magna. Nulla varius ornare odio. Donec accumsan mauris sit amet augue. Sed ligula lacus, laoreet non, aliquam sit amet, iaculis tempor, lorem. Suspendisse eros. Nam porta, leo sed congue tempor, felis est ultrices eros, id mattis velit felis non metus. Curabitur vitae elit non mauris varius pretium. Aenean lacus sem, tincidunt ut, consequat quis, porta vitae, turpis. Nullam laoreet fermentum urna. Proin iaculis lectus.

Sed mattis, erat sit amet gravida malesuada, elit augue egestas diam, tempus scelerisque nunc nisl vitae libero. Sed consequat feugiat massa. Nunc porta, eros in eleifend varius, erat leo rutrum dui, non convallis lectus orci ut nibh. Sed lorem massa, nonummy quis, egestas id, condimentum at, nisl. Maecenas at nibh. Aliquam et augue at nunc pellentesque ullamcorper. Duis nisl nibh, laoreet suscipit, convallis ut, rutrum id, enim. Phasellus odio. Nulla nulla elit, molestie non, scelerisque at, vestibulum eu, nulla. Ut odio nisl, facilisis id, mollis et, scelerisque nec, enim. Aenean sem leo, pellentesque sit amet, scelerisque sit amet, vehicula pellentesque, sapien.

Sed consequat tellus et tortor. Ut tempor laoreet quam. Nullam id wisi a libero tristique semper. Nullam nisl massa, rutrum ut, egestas semper, mollis id, leo. Nulla ac massa eu risus blandit mattis. Mauris ut nunc. In hac habitasse platea dictumst. Aliquam eget tortor. Quisque dapibus pede in erat. Nunc enim. In dui nulla, commodo at, consectetuer nec, malesuada nec, elit. Aliquam ornare tellus eu urna. Sed nec metus. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas.

Phasellus id magna. Duis malesuada interdum arcu. Integer metus. Morbi pulvinar pellentesque mi. Suspendisse sed est eu magna molestie egestas. Quisque mi lorem, pulvinar eget, egestas quis, luctus at, ante. Proin auctor vehicula purus. Fusce ac nisl aliquam ante hendrerit pellentesque. Class

aptent taciti sociosqu ad litora torquent per conubia nostra, per inceptos hymenaeos. Morbi wisi. Etiam arcu mauris, facilisis sed, eleifend non, nonummy ut, pede. Cras ut lacus tempor metus mollis placerat. Vivamus eu tortor vel metus interdum malesuada.

Sed eleifend, eros sit amet faucibus elementum, urna sapien consectetuer mauris, quis egestas leo justo non risus. Morbi non felis ac libero vulputate fringilla. Mauris libero eros, lacinia non, sodales quis, dapibus porttitor, pede. Class aptent taciti sociosqu ad litora torquent per conubia nostra, per inceptos hymenaeos. Morbi dapibus mauris condimentum nulla. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Etiam sit amet erat. Nulla varius. Etiam tincidunt dui vitae turpis. Donec leo. Morbi vulputate convallis est. Integer aliquet. Pellentesque aliquet sodales urna.

Nullam eleifend justo in nisl. In hac habitasse platea dictumst. Morbi nonummy. Aliquam ut felis. In velit leo, dictum vitae, posuere id, vulputate nec, ante. Maecenas vitae pede nec dui dignissim suscipit. Morbi magna. Vestibulum id purus eget velit laoreet laoreet. Praesent sed leo vel nibh convallis blandit. Ut rutrum. Donec nibh. Donec interdum. Fusce sed pede sit amet elit rhoncus ultrices. Nullam at enim vitae pede vehicula iaculis.

Class aptent taciti sociosqu ad litora torquent per conubia nostra, per inceptos hymenaeos. Aenean nonummy turpis id odio. Integer euismod imperdiet turpis. Ut nec leo nec diam imperdiet lacinia. Etiam eget lacus eget mi ultricies posuere. In placerat tristique tortor. Sed porta vestibulum metus. Nulla iaculis sollicitudin pede. Fusce luctus tellus in dolor. Curabitur auctor velit a sem. Morbi sapien. Class aptent taciti sociosqu ad litora torquent per conubia nostra, per inceptos hymenaeos. Donec adipiscing urna vehicula nunc. Sed ornare leo in leo. In rhoncus leo ut dui. Aenean dolor quam, volutpat nec, fringilla id, consectetuer vel, pede.

Nulla malesuada risus ut urna. Aenean pretium velit sit amet metus. Duis iaculis. In hac habitasse platea dictumst. Nullam molestie turpis eget nisl. Duis a massa id pede dapibus ultricies. Sed eu leo. In at mauris sit amet tortor bibendum varius. Phasellus justo risus, posuere in, sagittis ac, varius vel, tortor. Quisque id enim. Phasellus consequat, libero pretium nonummy fringilla, tortor lacus vestibulum nunc, ut rhoncus ligula neque id justo. Nullam accumsan euismod nunc. Proin vitae ipsum ac metus dictum tempus. Nam ut wisi. Quisque tortor felis, interdum ac, sodales a, semper a, sem. Curabitur in velit sit amet dui tristique sodales. Vivamus mauris pede, lacinia eget, pellentesque quis, scelerisque eu, est. Aliquam risus. Quisque bibendum pede eu dolor.

Donec tempus neque vitae est. Aenean egestas odio sed risus ullamcorper ullamcorper. Sed in nulla a tortor tincidunt egestas. Nam sapien tortor, elementum sit amet, aliquam in, porttitor faucibus, enim. Nullam congue suscipit nibh. Quisque convallis. Praesent arcu nibh, vehicula eget, accumsan eu, tincidunt a, nibh. Suspendisse vulputate, tortor quis adipiscing viverra, lacus nibh dignissim tellus, eu suscipit risus ante fringilla diam. Quisque a libero vel pede imperdiet aliquet. Pellentesque nunc nibh, eleifend a, con-

sequat consequat, hendrerit nec, diam. Sed urna. Maecenas laoreet eleifend neque. Vivamus purus odio, eleifend non, iaculis a, ultrices sit amet, urna. Mauris faucibus odio vitae risus. In nisl. Praesent purus. Integer iaculis, sem eu egestas lacinia, lacus pede scelerisque augue, in ullamcorper dolor eros ac lacus. Nunc in libero.

Fusce suscipit cursus sem. Vivamus risus mi, egestas ac, imperdiet varius, faucibus quis, leo. Aenean tincidunt. Donec suscipit. Cras id justo quis nibh scelerisque dignissim. Aliquam sagittis elementum dolor. Aenean consectetuer justo in pede. Curabitur ullamcorper ligula nec orci. Aliquam purus turpis, aliquam id, ornare vitae, porttitor non, wisi. Maecenas luctus porta lorem. Donec vitae ligula eu ante pretium varius. Proin tortor metus, convallis et, hendrerit non, scelerisque in, urna. Cras quis libero eu ligula bibendum tempor. Vivamus tellus quam, malesuada eu, tempus sed, tempor sed, velit. Donec lacinia auctor libero.

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Some notable problems presented themselves throughout the course of this work which could influence the usability of such a system in a practical sense. The Android **MotionEvent** class **getPressure()** method used to collect pressure data in our system does not always return a high granularity of values. The pressure values are sometimes grouped into large steps. There might, for example, be 8 steps between 0.0 and 1.0 on some devices. This is a problem for our system which uses these pressure values to understand user variability. The problem seems to be device dependent suggesting that the device drivers may have a role to play in decreasing the reported graininess of pressure. Another possibility might be the values reported by the sensors, Perhaps these sensors only report a small number of steps.

6. RELATED WORK
In [10] a physical unclonable function (PUF) composed of a human biometric and silicon biometric leading to a unique user device identity. This work demonstrates how the PUF may be used for authentication. The user is presented with a polyline draw on the touch screen. The user then traces this line. The human pressure exerted in the trace and the exact traced path profile captures a biometric of the user. The silicon variability is extracted in a similar way to our implementation through capacitive touch and sensor circuitry of the mobile device. Our work differs in that we derive a model of user behavior over time which describes how the user interacts with the soft keyboard. Comparatively [10] shows that, once trained for a particular challenge line, it is possible to differentiate pair of user, device from other pairs of user, device. In addition, we use discrete touchscreen events, key presses, while [10] uses continuous touchscreen events, swipes.

More good work done in the area of PUF's on mobile devices includes [11]. This work utilizes the silicon manufacture variability found in many different sensors combining them to create a model of the user. Again, the variability for this system also utilizes human biometrics. [11] uses data from the accelerometers, gyroscopes, and magnetometers to develop their model. By comparison, our system shows this may be done for touch screen interactions.

7. CONCLUDING REMARKS
The findings we have presented suggest that touch screen interactions may be used in order to distinguish a legitimate user of a mobile device apart from illegitimate users. Many current solutions utilize one-time authentication schemes These solutions do not provide sufficient protection in a mobile environment. This work represents a step toward a holistic approach toward mobile security, catering to threats existing in this environment.

This work presents as part of a positive trend in mobile security. Technologies part of this trend incorporate elements of the mobile environment, providing enhanced security by incorporating properties of the human user as part of the authentication. This approach is superior to exclusive use of things the user knows, because knowledge may be easily imitated while human biometrics can not.

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