Practical Padding Oracle Attacks

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Black Hat Europe, 2010

Requisite

XOR

$$0 \oplus 0 = 0$$

$$0 \oplus 1 = 1$$

$$1 \oplus 0 = 1$$

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Outline

1. Introduction
   - Review of CBC Mode
   - Padding Oracle attack
2. Finding padding oracles
   - Find potential padding oracles
   - Confirm the existence of padding oracles
3. Basic PO attacks
   - Cracking CAPTCHA
   - Decrypting JSF view states
4. Advanced PO attacks
   - Using PO to encrypt
   - Distributed cross-site PO attacks

CBC Mode

- CBC mode is a cryptography mode of operation for a block cipher.
- Allows encryption of arbitrary length data.
- Encryption and decryption are defined by:

$$C_i = e_K(P_i \oplus C_{i-1})$$

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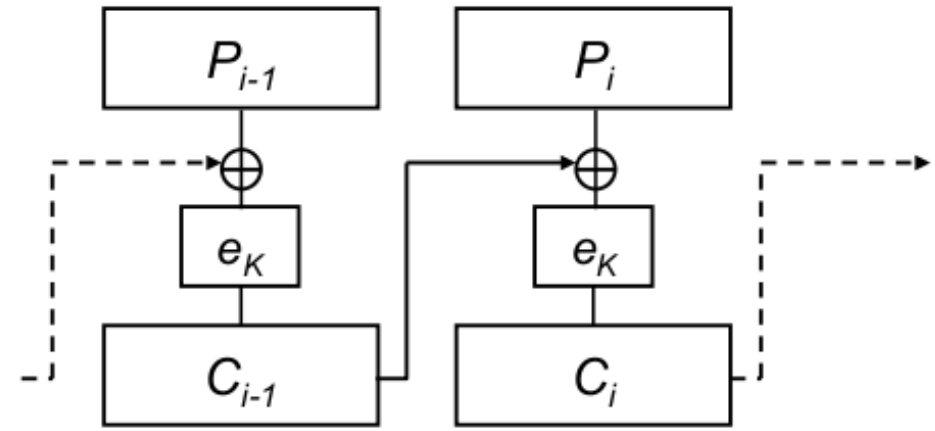
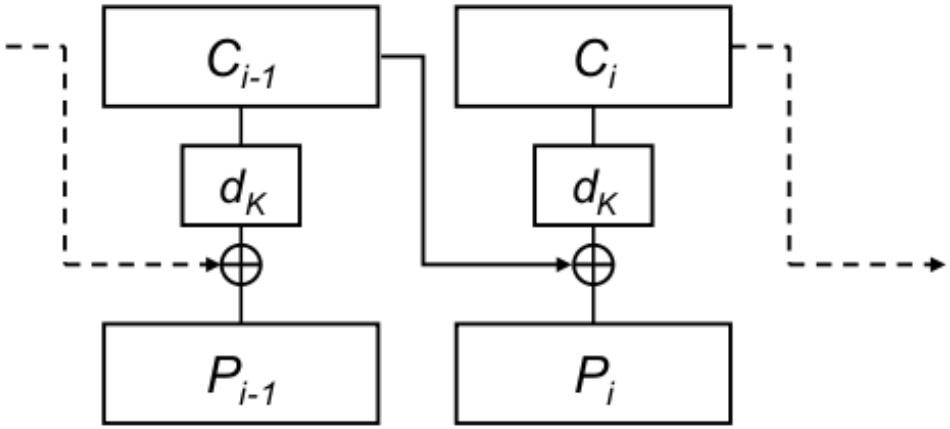
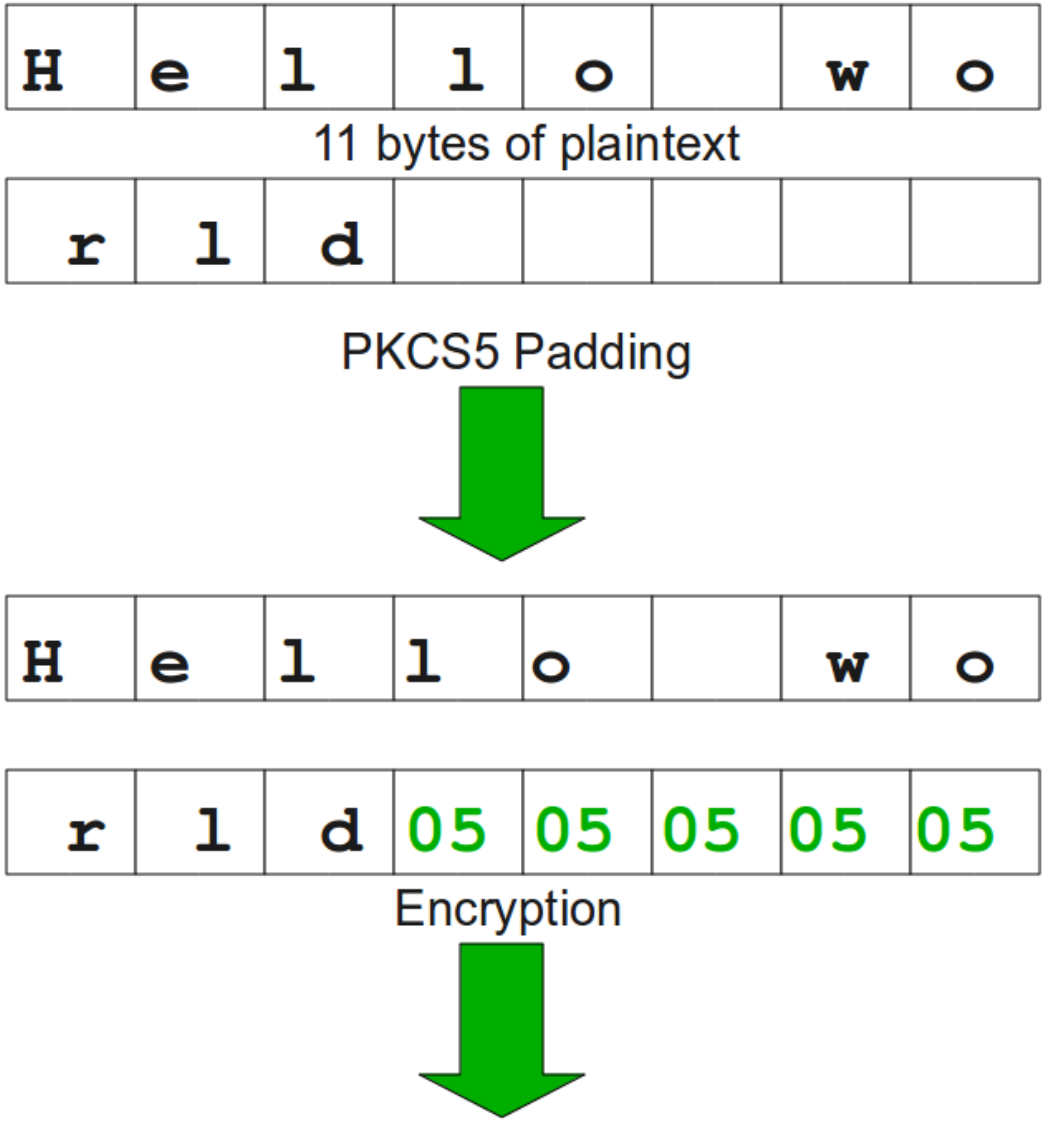


Typical block size n: 64 bits (DES, triple DES) or 128 bits (AES).



Typical key size: 56 bits (DES), 168 bits (triple DES), 128, 192 or 256 bits (AES).

Padding


H e l l o w o
11 bytes of plaintext
r l d
PKCS5 Padding
H e l l o w o
r l d 05 05 05 05 05
Encryption

Padding oracle attack

Introduction

- First introduced by Vaudenay at Eurocrypt 2002.
- Two assumptions:
  - Adversary can intercept padded messages encrypted in CBC mode.
  - Adversary has access to a padding oracle.

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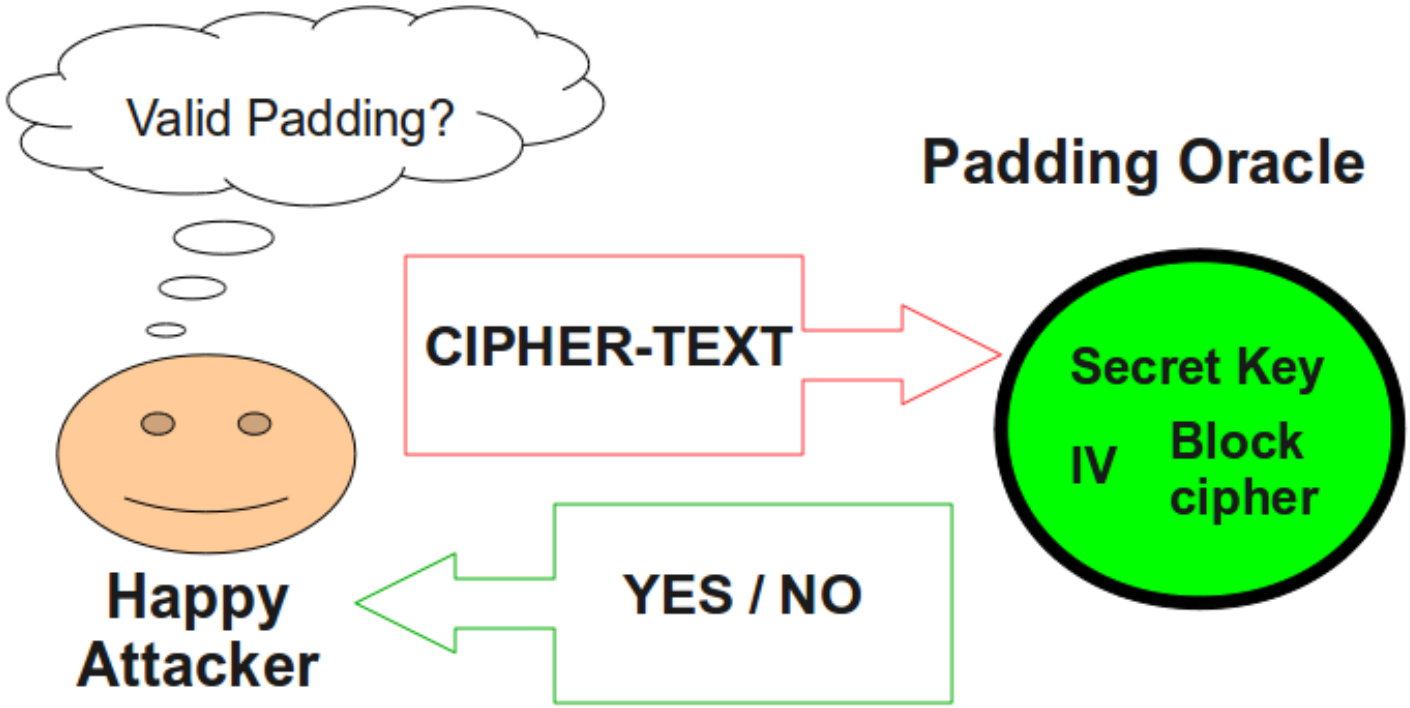

Padding oracle attack

What is a padding oracle?

- Adversary submits a CBC mode ciphertext C to oracle $\eth$.
- Oracle decrypts under fixed key K and checks correctness of padding.
- Oracle outputs VALID or INVALID according to correctness of padding:

$$\eth(C) = \begin{cases} 0, & \text{invalid} \\ 1, & \text{valid} \end{cases}$$

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Padding oracle attack

How does it work?

- For a long message, decrypt block by block. It's easy to parallelize the attack.
- For a block, decrypt the last byte first, then decrypt the next to last byte, and so on.
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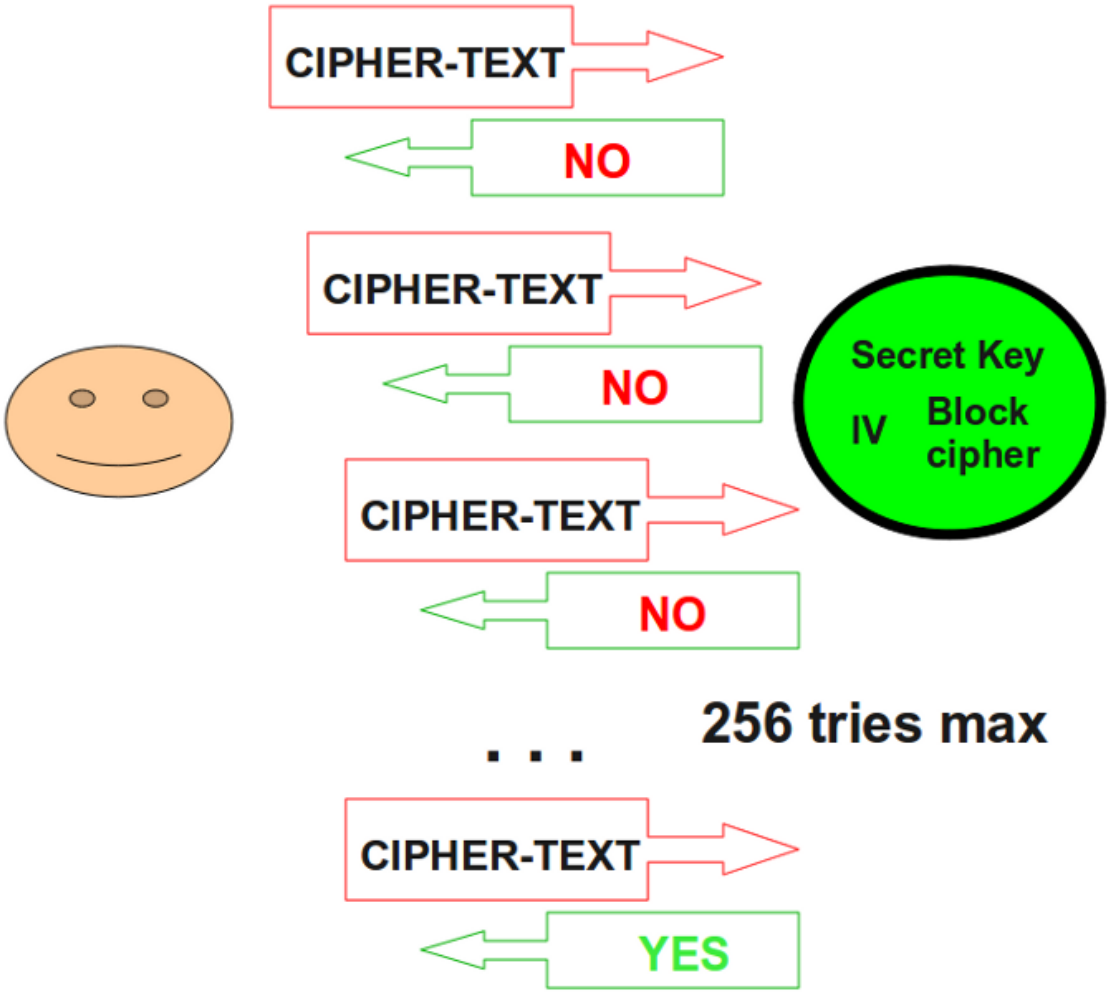
Padding oracle attack

How to decrypt a block



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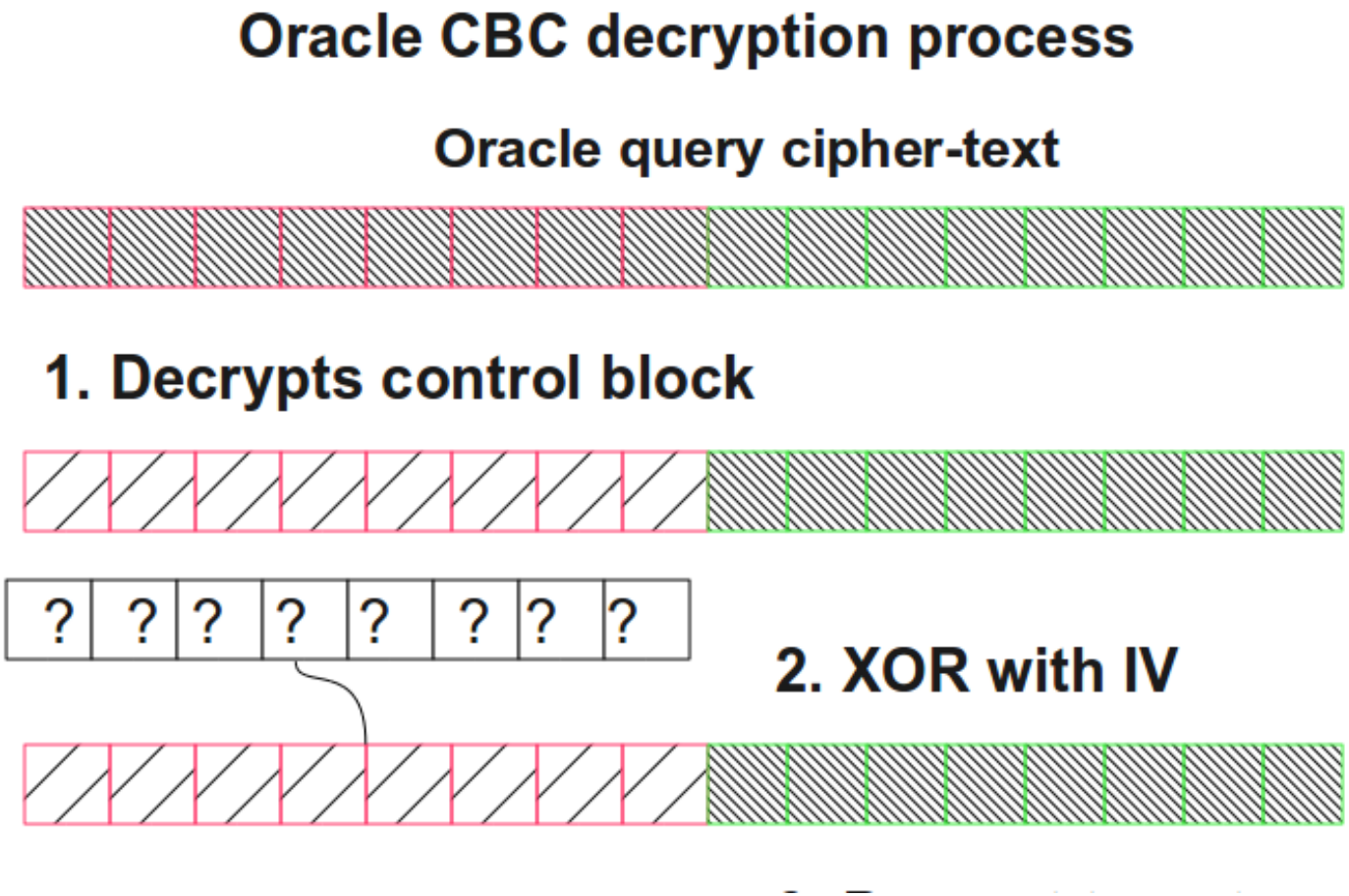

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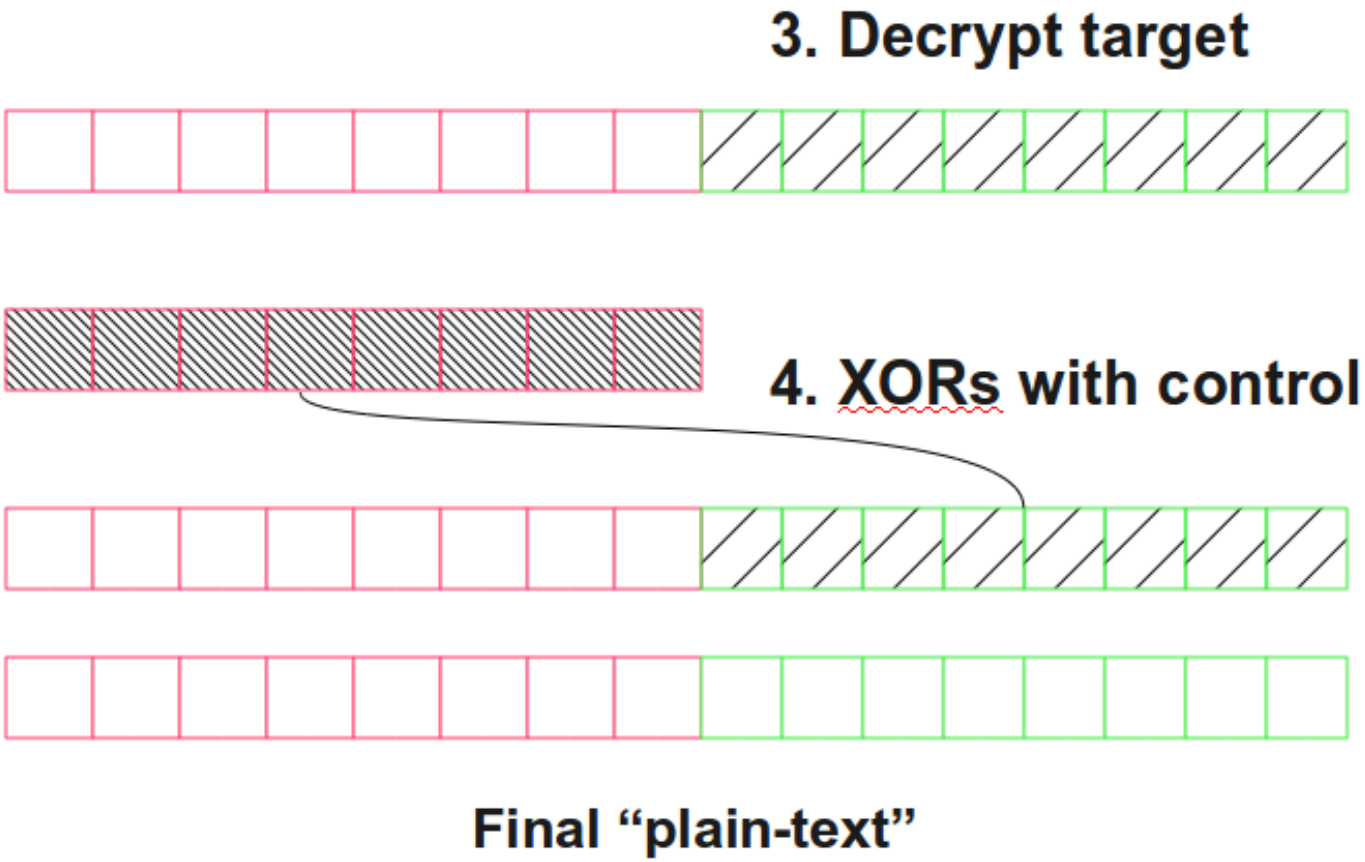

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Last byte decryption algorithm

Last byte decryption algorithm

- pick a few random bytes $r_1, ..., r_b$, and take $i = 0$.
- pick $r = r_1 r_2 ... r_{b-1} (r_b \oplus i)$.
- if $\mathcal{O}(r|y) = 0$ then increment i and go back to previous step.
- replace r_b by $r_b \oplus i$.
- for $n = b$ down to 2
  1. take $r = r_1 ... r_{b-n} (r_{b-1+1} \oplus 1) r_{b-n+2} ... r_b$
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- Vulnerability: **encrypt** and **decrypt** functions.
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Finding potential padding oracles

Blackbox testing

- Crawl the target to find BASE64 strings that look like a ciphertext.
- Replace a byte in the last block of the ciphertext by a random value, and send to the target.
- See if there is any error message. Even a blank page is enough information.

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Google hacking

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Source code auditing

- Look for code that imports low level cryptography libraries.
- Look for known source code keywords like **javax.crypto.BadPaddingException**.
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Confirm the existence of padding oracles

Determine the block size b

- All padding oracle attacks need a correct b.
- Most common block sizes are 8 and 16 bytes. Of course we can use trial and error.

How to determine the block size

- if $len(C)\%16 = 8$, then stop and output 8.
- take $y = C[-16:]$, i.e. y is the last sixteen bytes of C.
- if $\eth(C|y) = 1$, then stop and output 8.
- output 16.

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- Most important: know when the padding is VALID, and when it's INVALID.
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Confirm the existence of padding oracles

- Want to write your own tool to detect padding oracle? Follow this guideline (which is based on the algorithm in slide 22):
  - Determine the block size b.
  - Pick a few random words $r_1, ..., r_b$, and take $i = 0$.
  - Pick $r = r_1 r_2 ... r_{b-1} (r_b \oplus i)$.
  - Send $r|y$ to the target, where y is a valid ciphertext block. Record the value of i, content length, and content type of the response. Increment i, and go back to step 3 until $i > 255$.
  - Now you have 256 responses. If all of them are the same, then the target is not easily showing you that it is vulnerable to padding oracle attack.
  - Otherwise, look at each value of i where the responses are different from the rest. Examine carefully each response to see what happened.

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Cracking CAPTCHA

A broken CAPTCHA system

- $ERC = e_{K,IV}(rand())$.
- ......
- ERC is stored as either a hidden field or a cookie in the CAPTCHA form.
- Once a user submits, the server decrypts ERC, and compares it with the code that the user has entered. If equal, the server accepts the request; it denies the request otherwise.

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Bypass the broken CAPTCHA system

- Since the system decrypts any *ERC* sent to it, it is vulnerable to Padding Oracle attack.
- The only remaining problem now is to know when padding is VALID, and when it's not.
- Fortunately, most CAPTCHA systems would send back an error notification when they fail to decrypt *ERC*, i.e. padding is INVALID.
- In addition, when we modify *ERC* so that the padding is VALID, most systems would display an image with a broken code.
- Now we have a padding oracle, and we can use it to decrypt any *ERC*, thus bypass the CAPTCHA completely.

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- If the IV is secret, we can't know P_0, thus can't crack CAPTCHA systems whose P_0 contains part of the random code.
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Demo

Cracking CAPTCHA

- Target: http://www.bidz.com
- We can control the IV.

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Decrypting JSF view states

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Padding oracle in JSF frameworks

- By default, all JSF frameworks would display a very detailed error message if it fails to decrypt a view state.

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- if we see **javax.crypto.BadPaddingException**, then it's INVALID padding
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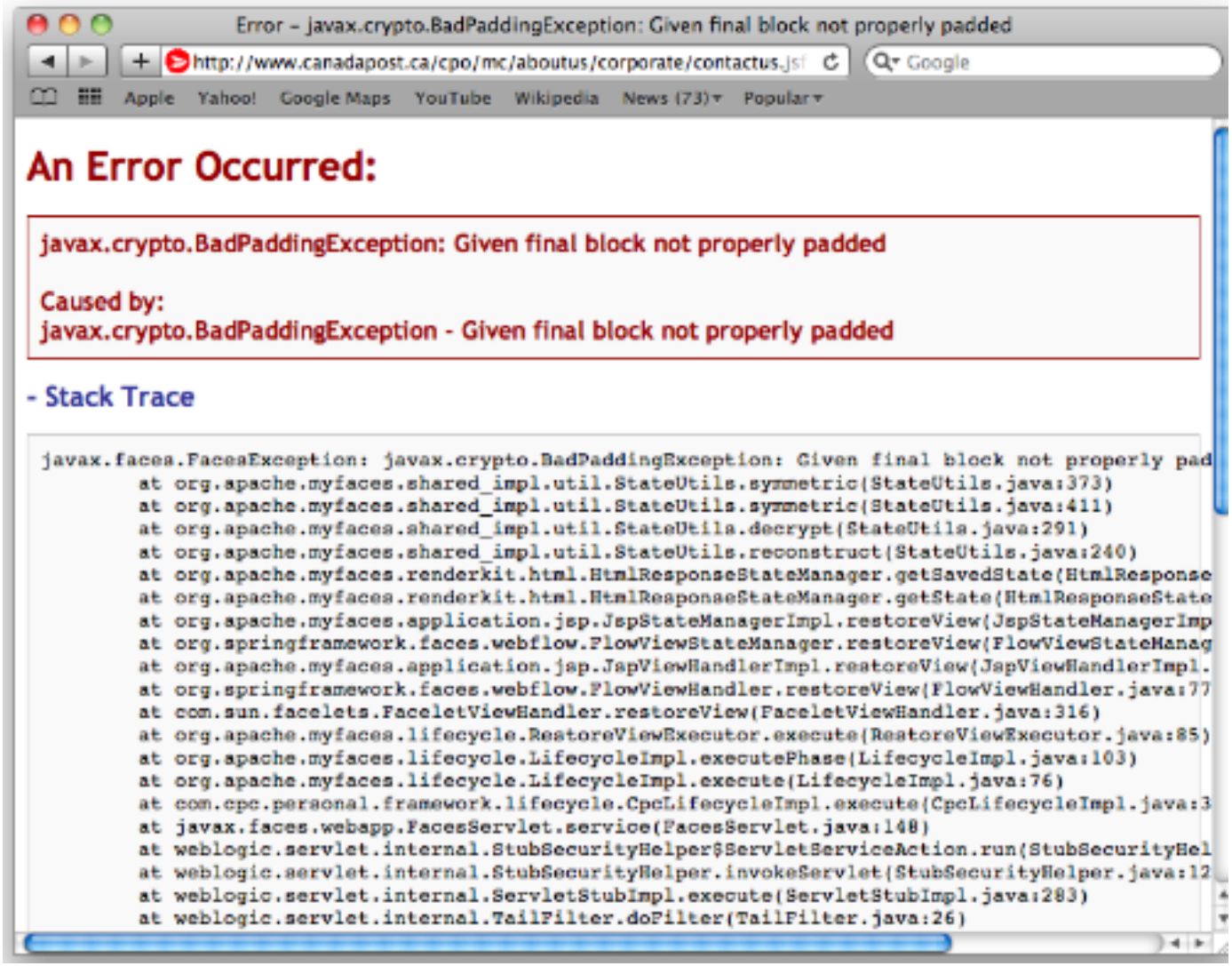
Apache MyFaces error-page



Decrypting JSF view states

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- Most JSF frameworks allow developers to turn off error messages. Then we can use the following simple trick:

Padding oracle in JSF frameworks when error-page is turned off

- Say we want to decrypt block C_i of an encrypted view state $C_0|C_1|...|C_{n-1}$, then we send $C_0|C_1|...|C_{n-1}|C_{random}|C_i$ to the target.
- Since Java ignores those extra blocks while decrypting and deserializing view states, it's VALID padding if the target returns the same page as when the view state is unaltered.
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Using PO to encrypt

An introduction to CBC-R

- CBC-R turns a decryption oracle into an encryption oracle.
- We all know that CBC decryption works as following:

$$P_i = d_K(C_i) \oplus C_{i-1}$$

$$C_0 = IV$$

- We can use a padding oracle to get $d_K(C_i)$, and we control C_{i-1}. In other words, we can produce any P_i as we want.

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How CBC-R works

CBC-R pseudocode

- choose a plaintext message $P_0|...|P_{n-1}$ that you want to encrypt.
- pick a random C_{n-1}.
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- output $IV|C_0|C_1|...|C_{n-1}$. This ciphertext would be decrypted to $P_0|...|P_{n-1}$.

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- CBC-R allows us to encrypt any message, but if we cannot set the IV, then first plaintext block P_0 will be random and meaningless.
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- $P_{valid} = d_K(C_{captured}|IV_{CBC-R}|P_{CBC-R})$.
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CBC-R Applications

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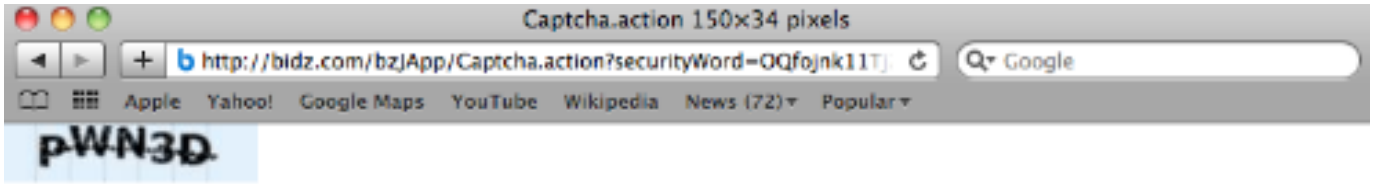

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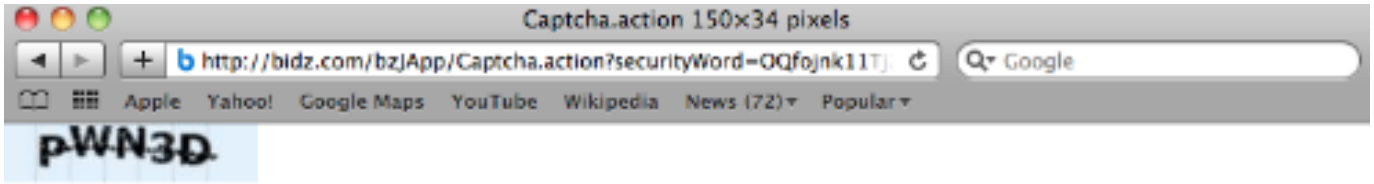

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- Only a single bit of information is necessary to exploit a padding oracle.
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