Padding Oracles Everywhere

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Outline

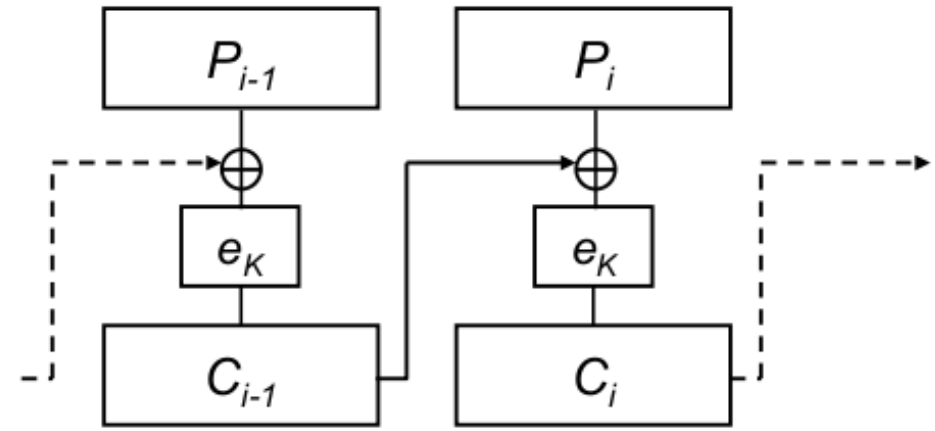
CBC Mode

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

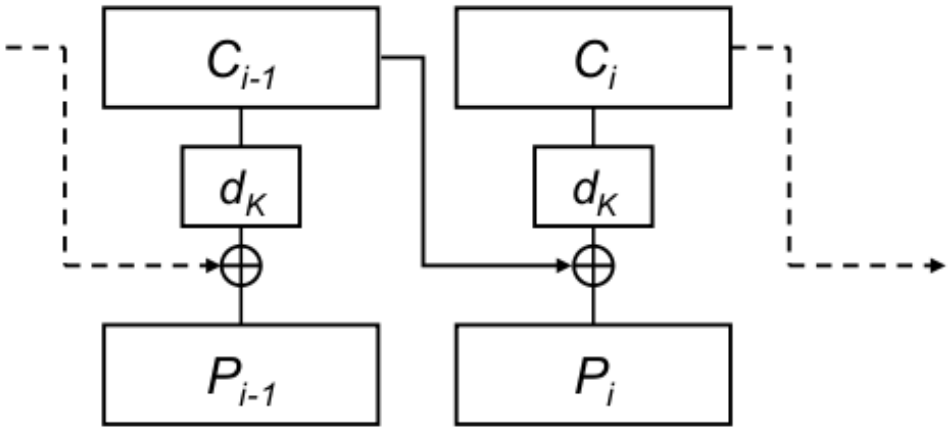
$$C_i = e_K(P_i \oplus C_{i-1})$$

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

CBC Mode

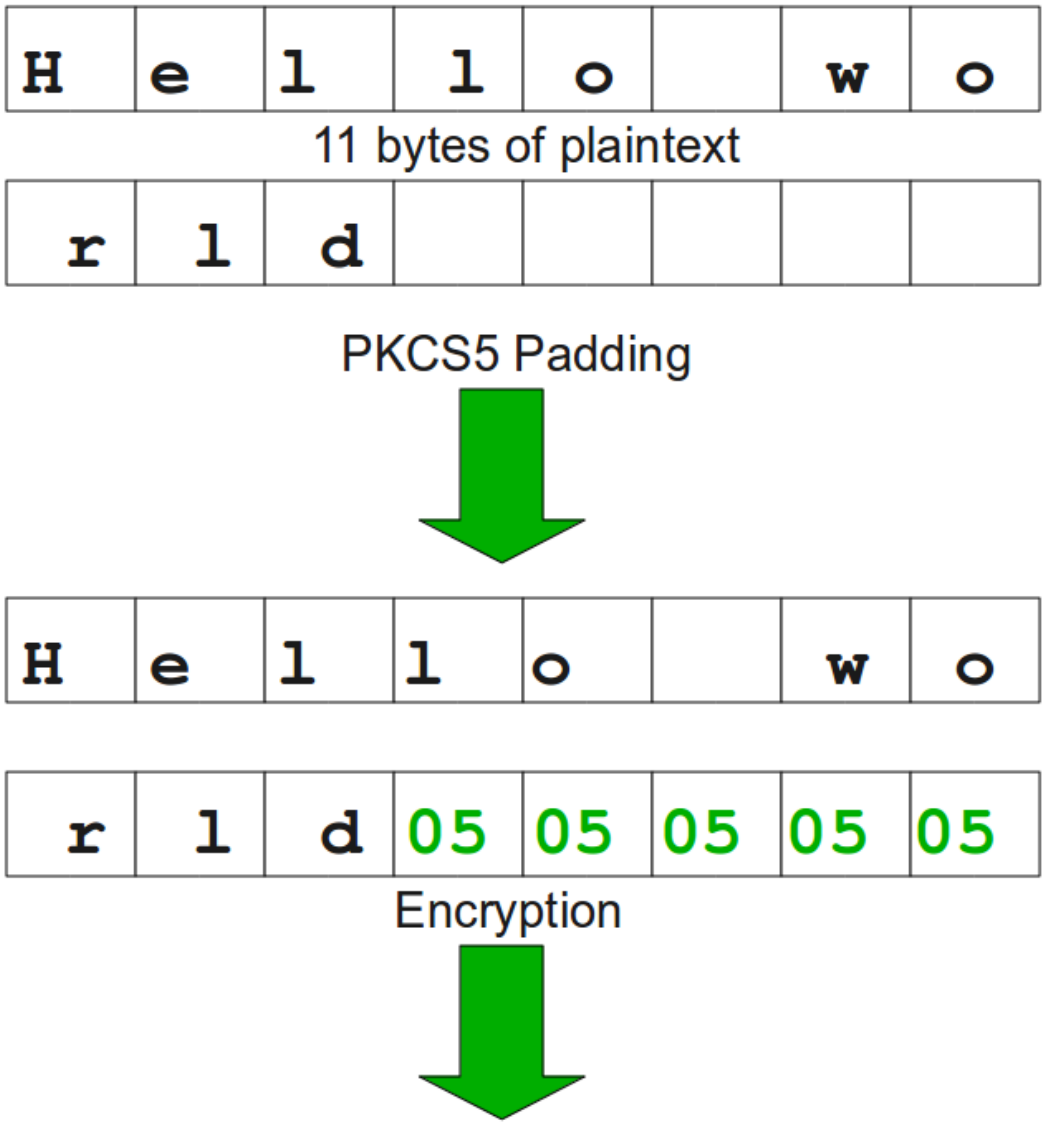


Typical block size n: 64 bits (DES, triple DES) or 128 bits (AES).



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

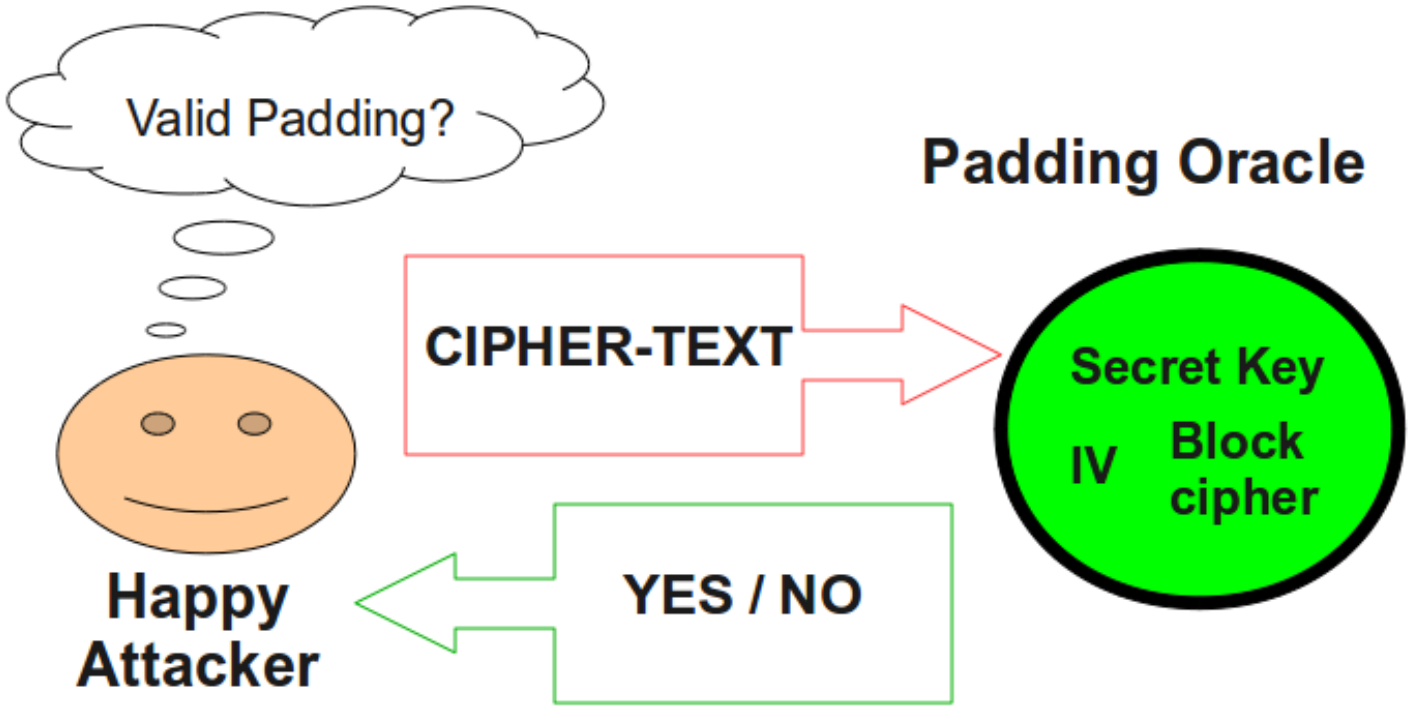
Padding oracle attack

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.

Padding oracle attack

What is a padding oracle?



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:

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

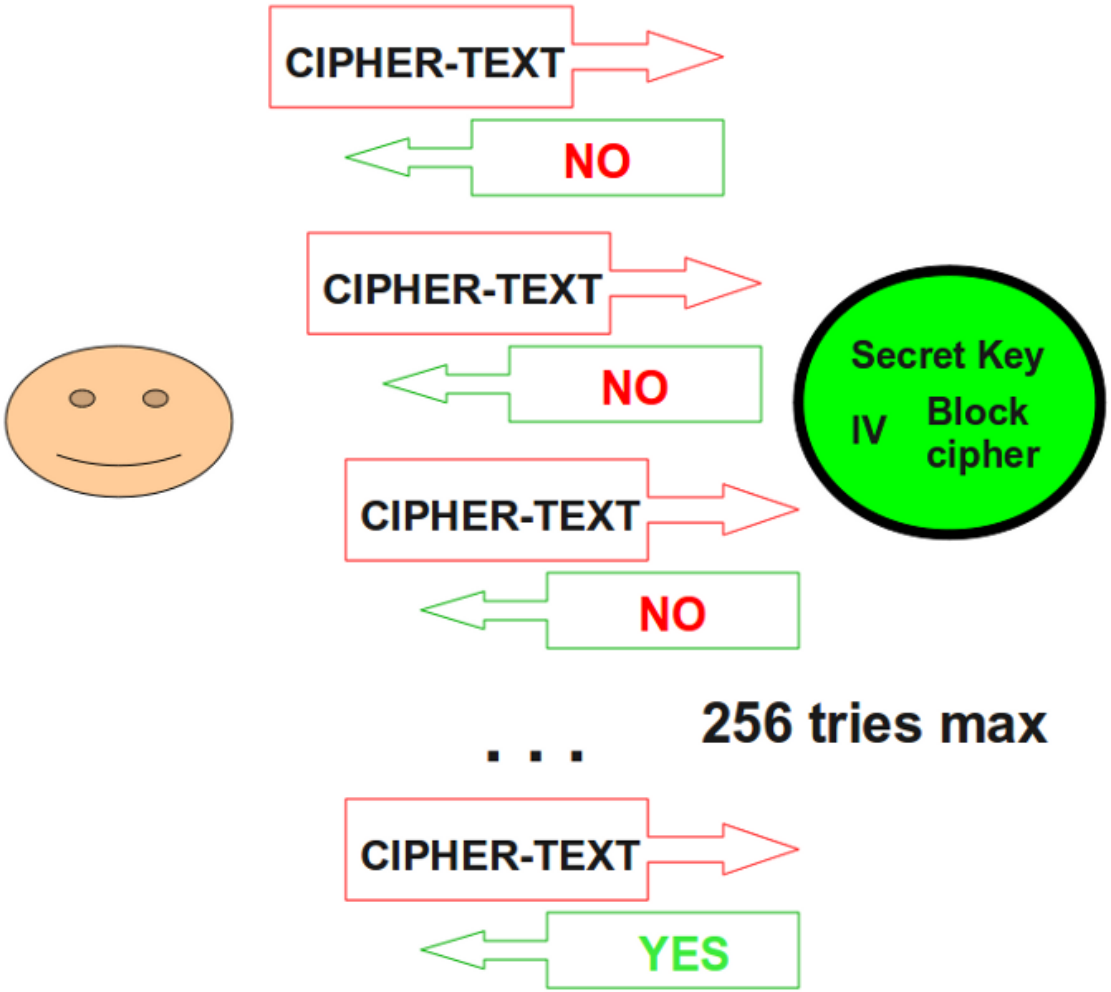
Padding oracle attack

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.
- How?

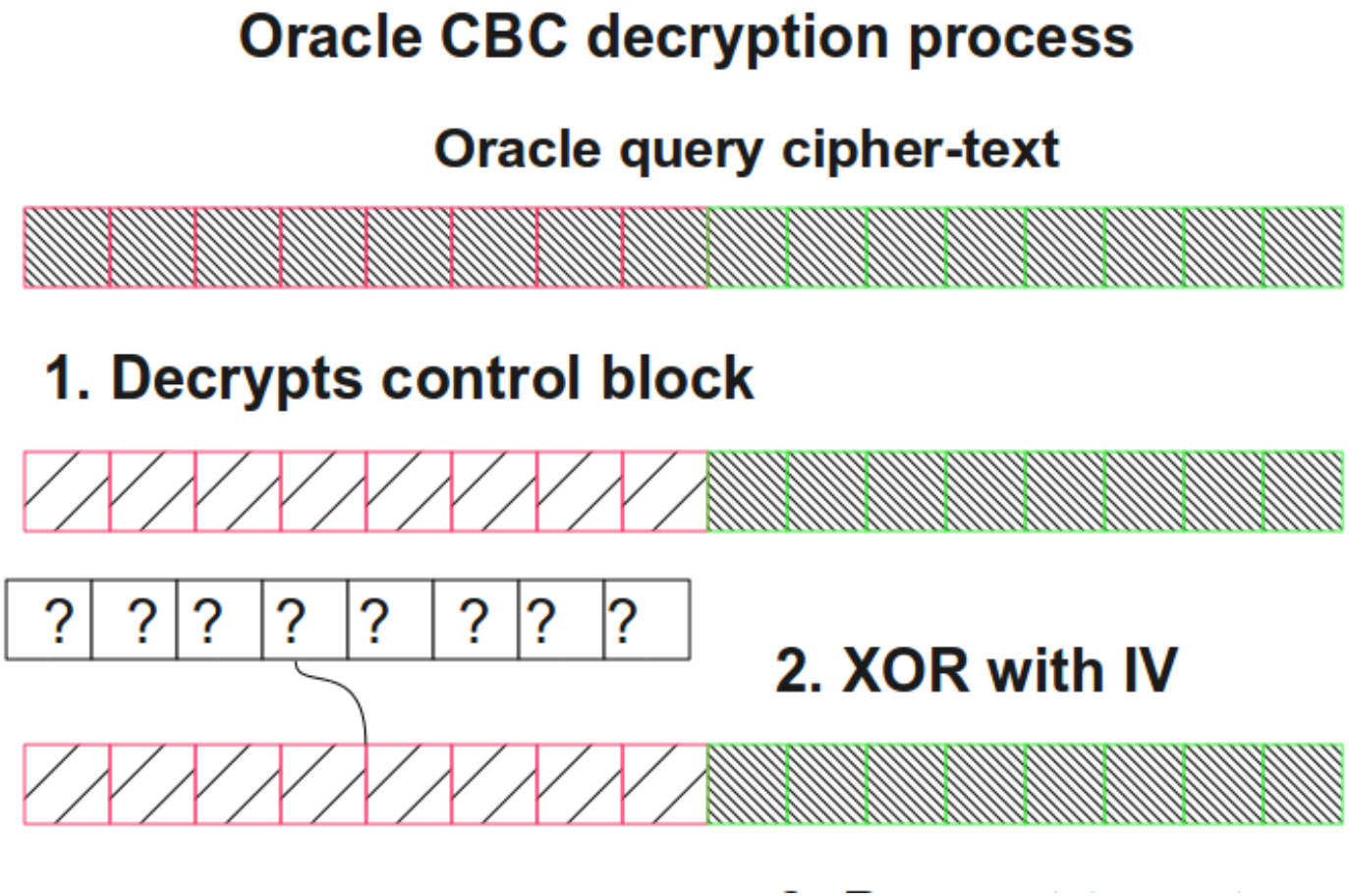
Padding oracle attack

How to decrypt a block



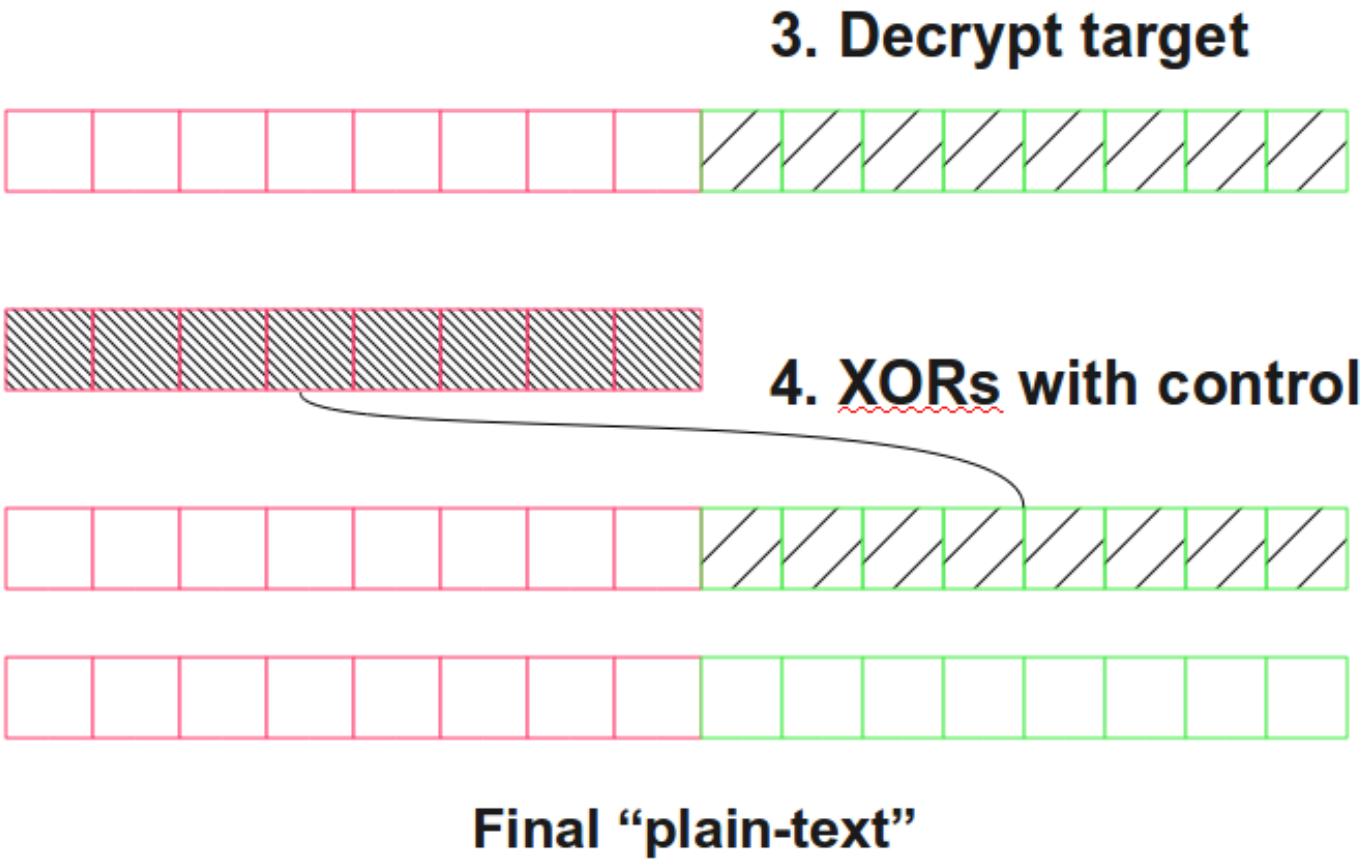
Padding oracle attack

How to decrypt a block



Padding oracle attack

How to decrypt a block



Padding oracle attack

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 $\eth(r|y) = 0$ 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 $r = r_1 ... r_{b-n}(r_{b-1+1} \oplus 1) r_{b-n+2} ... r_b$
    2. if $\eth(r|y) = 0$ then stop and output $(r_{b-n+1} \oplus n) ... (r_b \oplus n)$
  - output $r_b \oplus 1$.

POET vs 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.

POET vs CAPTCHA

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.

POET vs JavaServer Faces

Introduction

- JavaServer Faces (JSF) is a popular Java-based standard for building server-side user interfaces.
- Like ASP.NET, JSF stores the state of the view in a hidden field.
- Although JSF specification advises that view state should be encrypted and tamper evident, but no implementation follows that advice.
- In other words, we can use padding oracle attacks to decrypt the view states of most JSF frameworks.

POET vs JavaServer Faces

Padding oracle in JSF frameworks

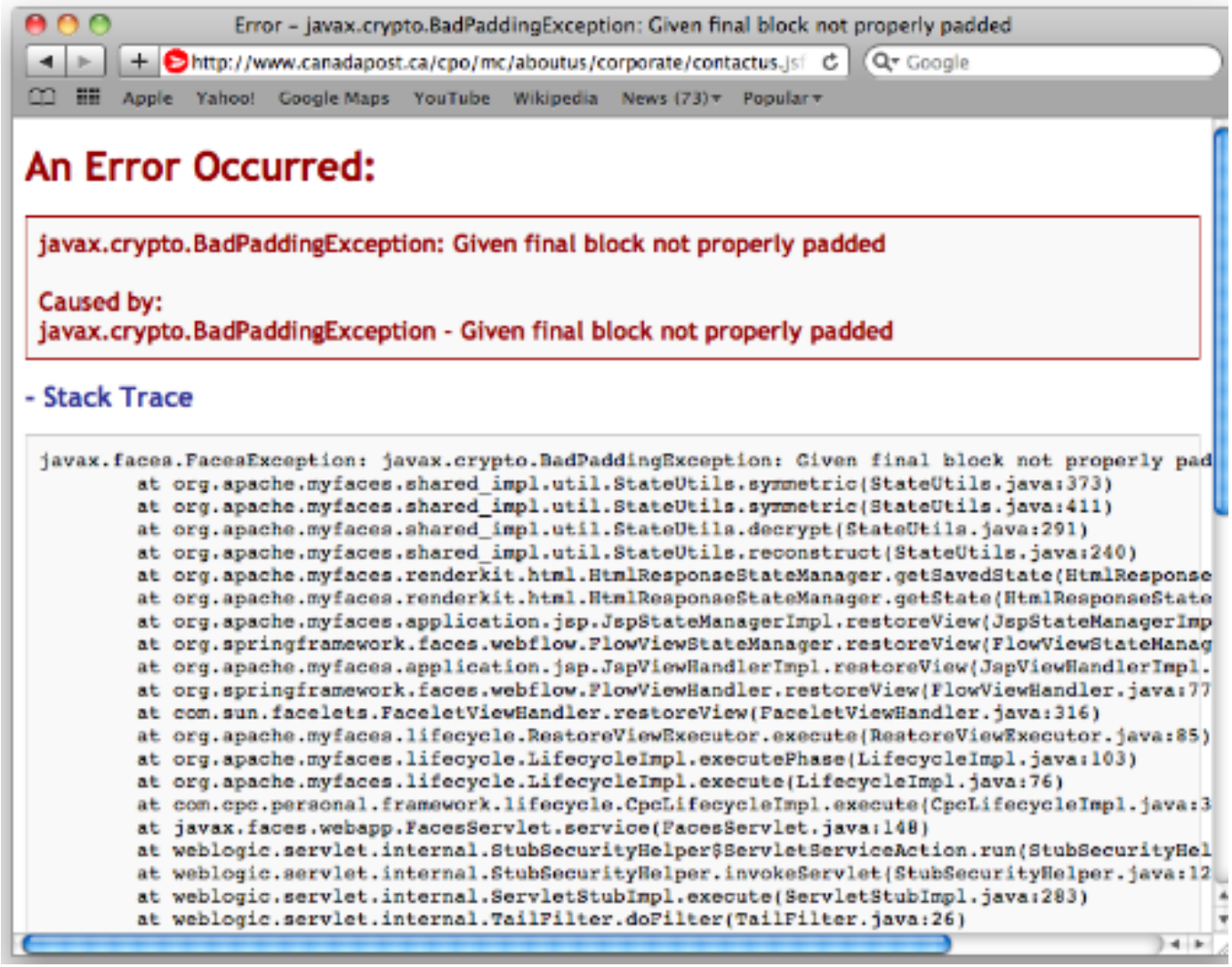
- By default, all JSF frameworks would display a very detailed error message if it fails to decrypt a view state.

Padding oracle in default installations of JSF frameworks

- if we see **javax.crypto.BadPaddingException**, then it's INVALID padding
  - it's VALID padding otherwise.

POET vs JavaServer Faces

Apache MyFaces error-page



POET vs JavaServer Faces

Padding Oracle in JSF frameworks

- 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.
  - And it's probably INVALID padding if we see something else, e.g. a HTTP 500 error message.

Demo

POET vs Apache MyFaces

- Apache MyFaces latest version.
- This also works with SUN Mojarra and probably other JSF implementations.

Distributed cross-site PO attacks

- Only a single bit of information is necessary to exploit a padding oracle.
- Cross-domain information leakage bugs in web browsers can help.
- One example: <img> + onerror()/onload() events.
- onLoad() called: VALID padding; onError() called: INVALID padding.

Distributed cross-site PO attacks

- We've been able to exploit CAPTCHA schemes using a single Javascript program running in the local browser
- Creating a distributed attack is as simple as injecting javascript code into popular websites.
- Distributed attacks allows easy creation of code books.

Demo

Distributed cross-site PO attacks

- Cracking CAPTCHA using Javascript running locally.
- Target: http://www.bidz.com.

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.

Using PO to encrypt

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}.
  - for $i = n-1$ down to 1: $C_{i-1} = P_i \oplus d_{\eth}(C_i)$
  - $IV = P_0 \oplus d_{\eth}(C_0)$
  - output $IV|C_0|C_1|...|C_{n-1}$. This ciphertext would be decrypted to $P_0|...|P_{n-1}$.

Using PO to encrypt

CBC-R Without Controlling IV

- 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.
- If the victim expects the decrypted message to start with a standard header, then it will ignore the forged message constructed by CBC-R.
- We have not found generic way to overcome this limitation. However, we have found workarounds for particular cases.

Using PO to encrypt

CBC-R Without Controlling IV

Using captured ciphertexts as prefix

- $P_{valid} = d_K(C_{captured}|IV_{CBC-R}|P_{CBC-R})$.
  - The block at the position of IV_{CBC-R} is still garbled.
  - We can make the garbled block becomes part of some string that doesn't affect the semantic of the message such as comment or textbox label.

Using PO to encrypt

CBC-R Without Controlling IV

Brute-forcing C_0

- CBC-R can produce many different ciphertexts that decrypted to the same plaintext block chain $P_{n-1}, ..., P_1$. The only difference is the first plaintext block which is computed as following:

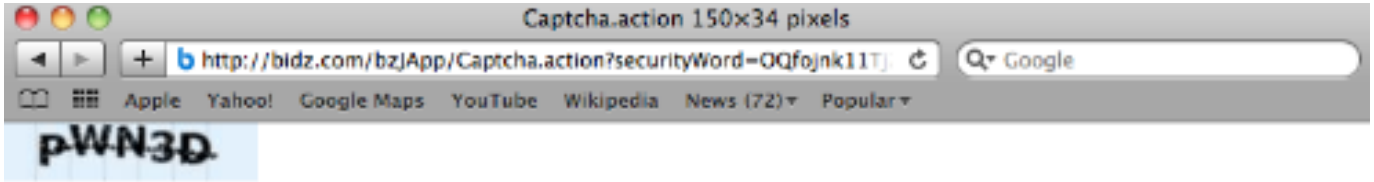
$$P_0 = d_K(C_0) \oplus IV$$

  - A valid header means that the first few bytes of P_0 must match some magic numbers. There are also systems that accept a message if the first byte of its P_0 matches its size.
  - If this is the case, and if the message is short enough, we can try our luck by brute-forcing C_0.

Using PO to encrypt

CBC-R Applications

sudo make me a CAPCHA



Using PO to encrypt

CBC-R Applications

Creating malicious JSF view states

- Which view states to create?
  - How to solve the garbled block problem?

ASP.NET's design problems

Web.config (We steal this slide from Paul Craig)

- The Golden Rule of Web Security: "Do not keep anything sensitive inside the document root."
- Web.config is the most important and sensitive file in ASP.NET.
- Guess what? It's just a normal file inside the document root!
  - Usernames, passwords, connection strings.
  - MachineKey: validationKey (HMAC key) and decryptionKey (DES, 3DES, or AES key).
  - A lot of configuration information.
- All it takes is one file disclose vulnerability.

ASP.NET's design problems

Cryptography

- MAC-then-Encrypt -> Decrypt-then-Verify -> still leak padding vadility information.
- Crypto API does not authenticate messages by default -> there are some encryptions w/o using MAC at all.
- Fixed known IV.
- MachineKeyCompatibilityMode.Framework20SP2.
- Same keys use to encrypt a lot of different things -> one padding oracle leads to full compromise.
- No easy way to generate keys:
  - People don't change keys during the lifetime of applications.
  - People don't change default keys in downloaded applications.
  - People even generate keys using online tools.

Padding oracles in ASP.NET

MAC-then-Encrypt: FAILED

- ASP.NET MAC-then-Encrypt these things:
  - ViewStates.
  - Form Authentication Tickets.
  - Anonymous Identification.
  - Role Cookies.
- In other words, universial padding oracles in every ASP.NET application!

Padding oracles in ASP.NET

No MAC at all: EPIC FAILED

- ASP.NET does not use MAC at all when encrypting:
  - WebResource
- Even better universial padding oracle!

Padding oracles in ASP.NET

How to detect padding oracles in ASP.NET

- Nice error messages, often turned on by default.
- No error message? Nice HTTP response statuses.
- Always the same 404 status? Nice timing information.

DEMO

POET vs ASP.NET

- 0-day: works for the latest versions of ASP.NET.
- Target application: DotNetNuke (over 600,000 public installations).
- POET -> remote code execution -> Cesar's Token Kidnapping -> ROOT privilege on Windows.

What happened?

- This line is worth the price of admission: we found a way to read arbitrary files using CBC-R!
- You may need to optimize your CBC-R attack. Full paper and tools will be released soon!

Summary

- Padding oracle attacks allow one to decrypt ciphertext without knowing the key.
- We can use padding oracle attacks to crack CAPTCHA, and decrypt JSF view state, etc.
- Distributed cross-site padding oracle attacks allow one to distributively build a code book to map all ciphertexts to corresponding plaintexts.
- CBC-R turns a decryption oracle into an encryption oracle, and allow us to destroy ASP.NET security.