Zombie POODLE, GOLDENDOODLE, & How TLSv1.3 Can Save Us All

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Presentation Overview

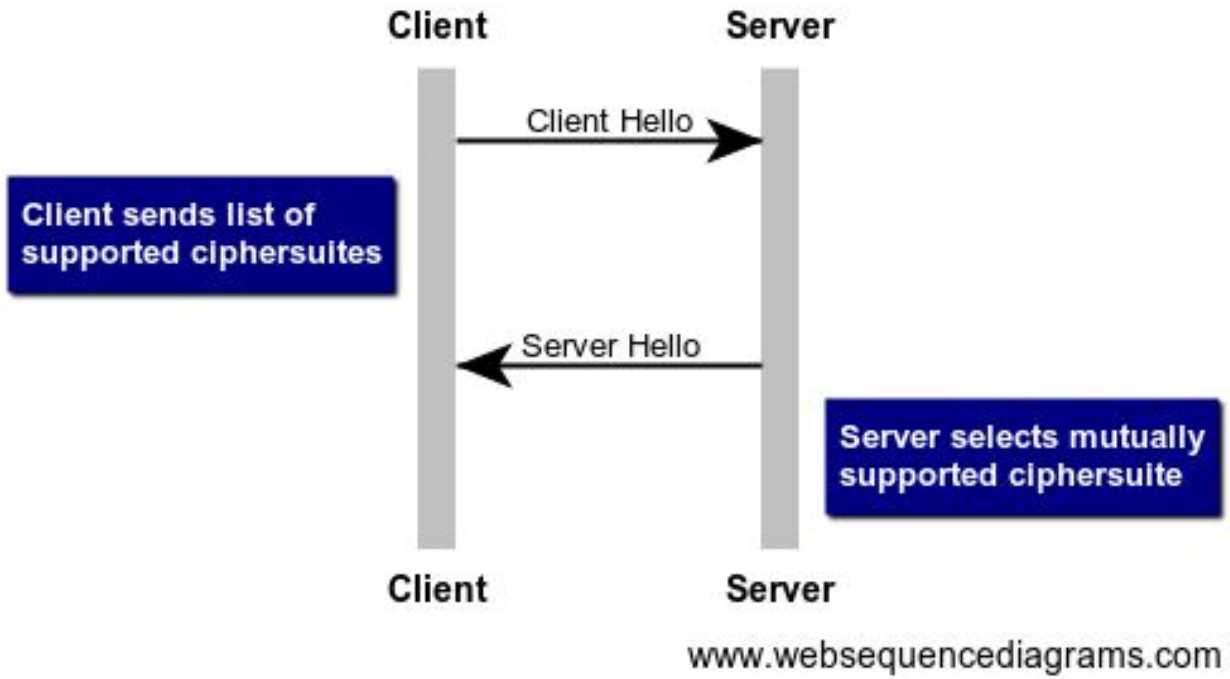
- TLS/CBC Encryption Primer
- Padding Oracle Exploitation
- Scanning For Padding Oracles
- Zombie POODLE & GOLDENDOODLE
- How TLS 1.3 Can Save Us All

SSL/TLS Primer

TLS enables private communication over non-private links.

SSL/TLS Primer

Hello Messages Determine **Ciphersuite** Selection



What is a Ciphersuite?

Set of algorithms for securing an SSL/TLS session

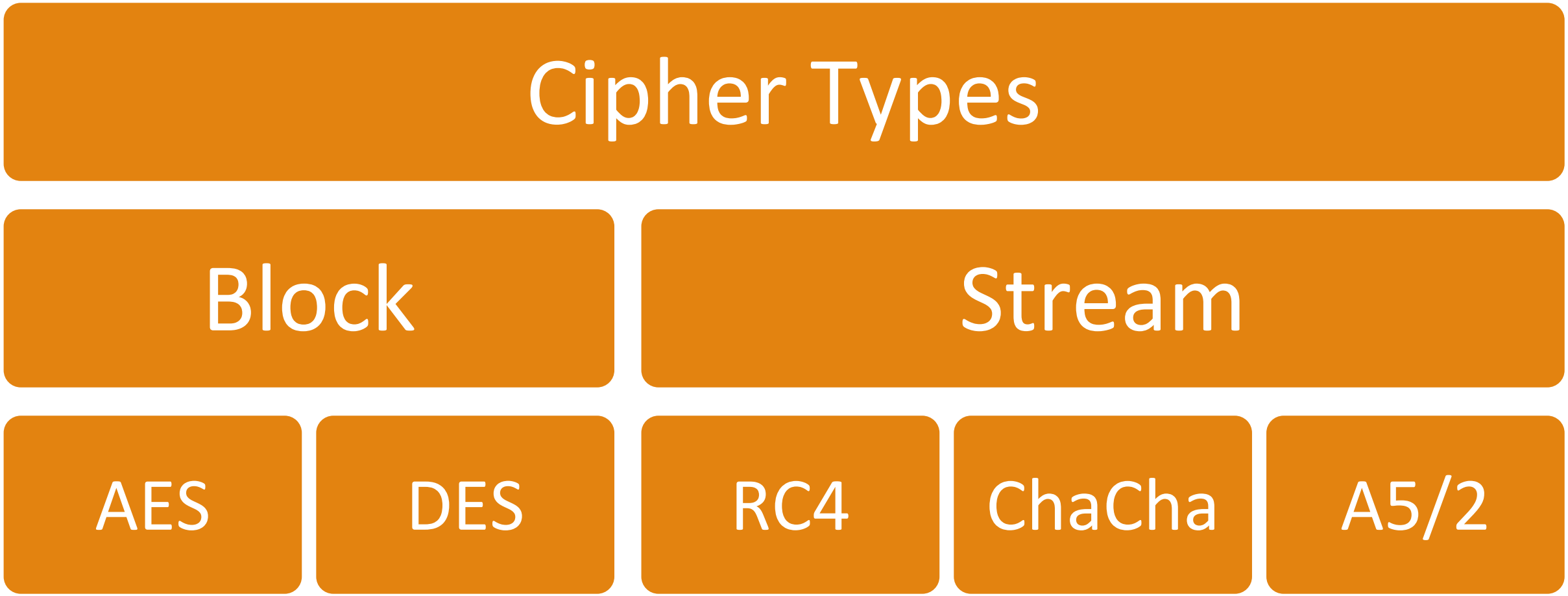
- Key Exchange / Authentication
- Message Encryption
- Message Authentication

Message Encryption

Message encryption is the transformation of plaintext into ciphertext (and back again).

- Message encryption is the focus of this presentation 😊

Message Encryption



Block Ciphers

Fixed-length inputs only

- DES (64-bit blocks)
- AES (128-bit blocks)
- Blowfish (32-bit blocks)

Block Cipher Padding

Cipher only works on a *block*

Incomplete blocks get filled with “padding”

Block Cipher Mode of Operation

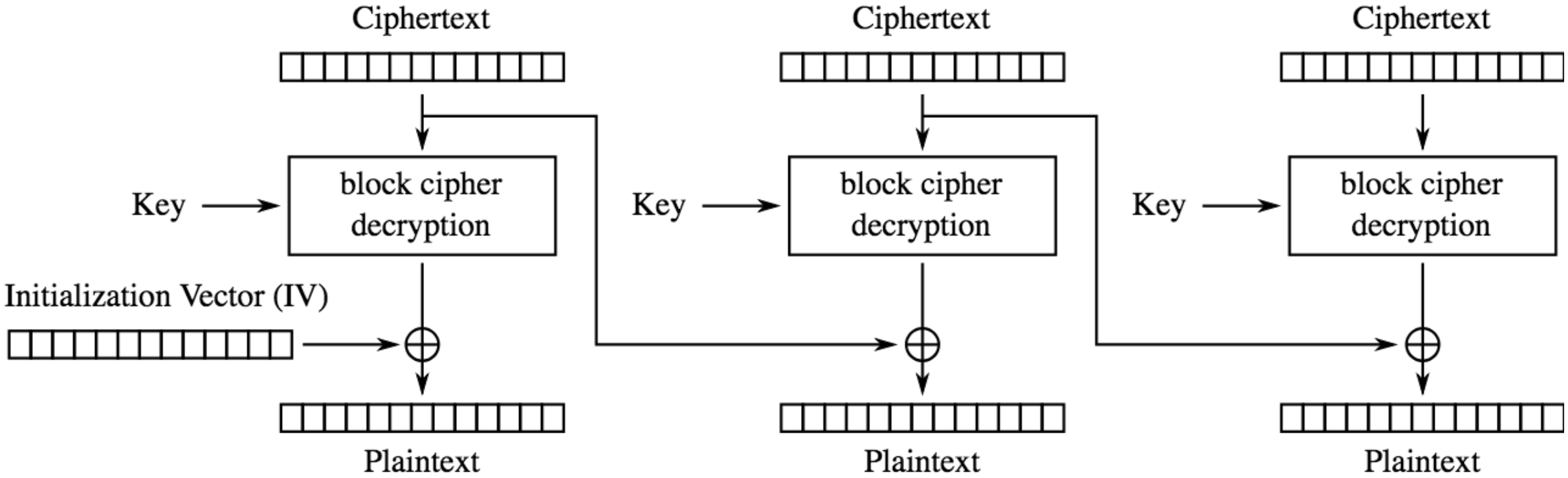
Cipher Mode Defines How To Encrypt Multiple Blocks

SSL/TLS Encryption Primer

Block Cipher Modes

CBC | ECB | CTR | CFB | GCM

Today's Villain: CBC Mode

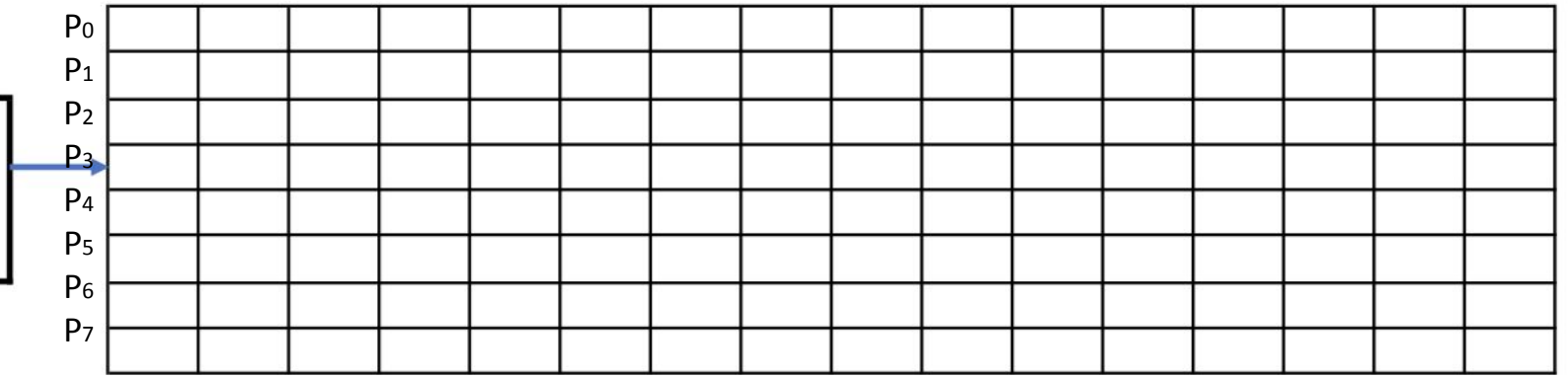


Cipher Block Chaining (CBC) mode decryption

Let’s do an example…

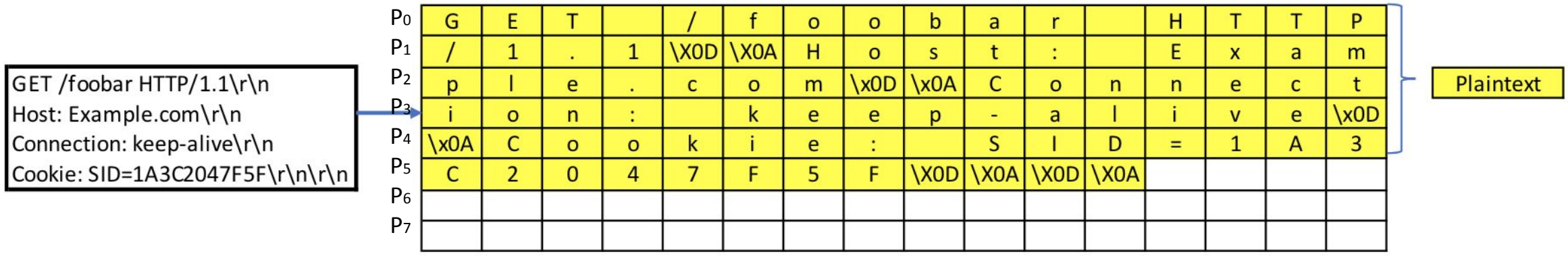
TLS CBC Padding Walkthrough

```
GET /foobar HTTP/1.1\r\n
Host: Example.com\r\n
Connection: keep-alive\r\n
Cookie: SID=1A3C2047F5F\r\n\r\n
```



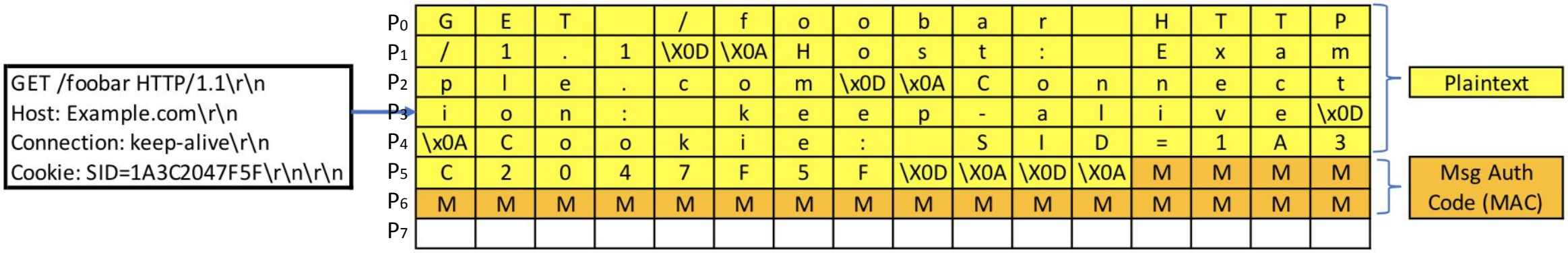
16-Bytes/Block for AES

TLS CBC Padding Walkthrough



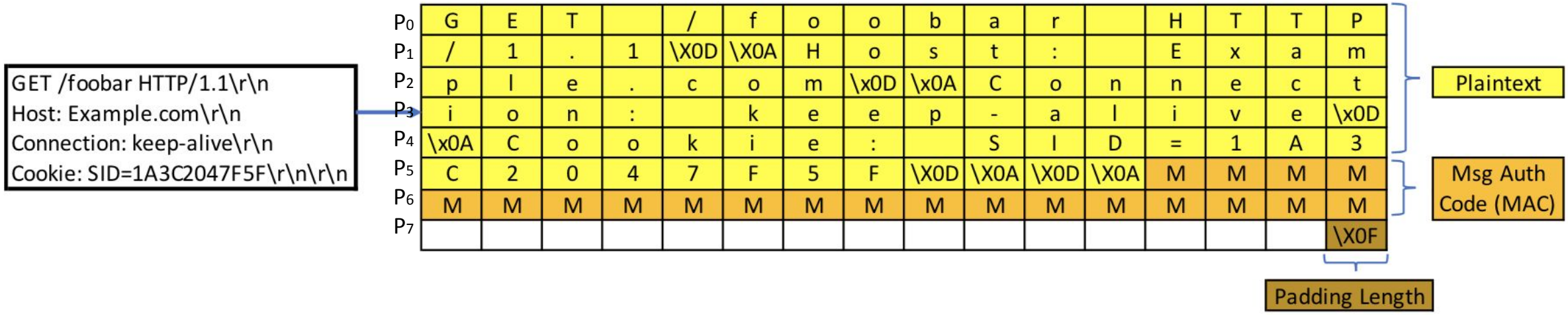
1) Split request into 16-byte blocks (AES)

TLS CBC Padding Walkthrough



2) Append Message Authentication Code (MAC)
(This is 20 bytes for SHA, but SHA256 uses a 32-byte MAC.)

TLS CBC Padding Walkthrough



3) Required padding length* is determined and set

*NOTE: Padding length byte is not counted as a pad byte

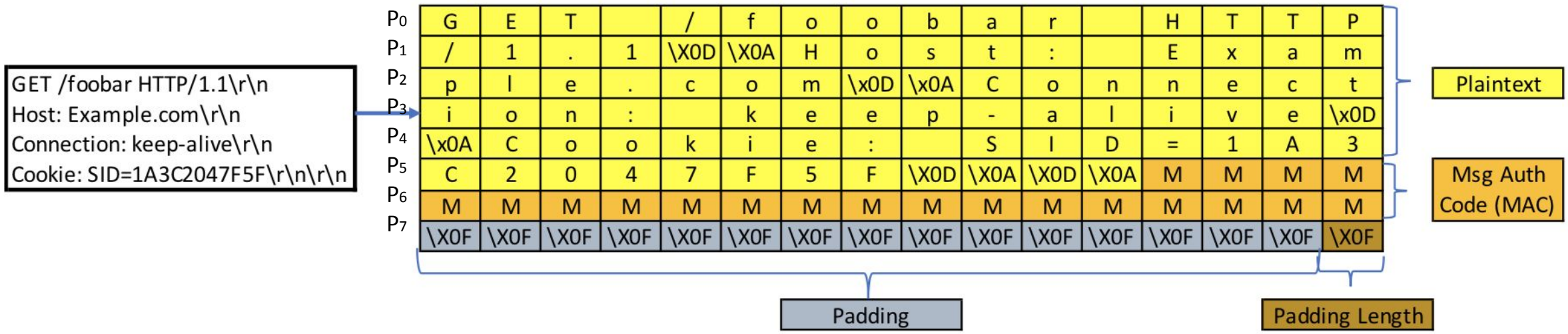
Padding Byte Values

For SSLv3, padding bytes are **random**:

Padding Byte Values

For TLS, pad values must match the pad length:

TLS CBC Padding Walkthrough



4) *n* padding bytes are added with value *n*

TLS CBC Mode Encryption

P_0	G	E	T		/	f	o	o	b	a	r		H	T	T	P
P_1	/	1	.	1	\X0D	\X0A	H	o	s	t	:		E	x	a	m
P_2	p	l	e	.	c	o	m	\x0D	\x0A	C	o	n	n	e	c	t
P_3	i	o	n	:		k	e	e	p	-	a	l	i	v	e	\x0D
P_4	\x0A	C	o	o	k	i	e	:		S	l	D	=	1	A	3
P_5	C	2	0	4	7	F	5	F	\X0D	\X0A	\X0D	\X0A	M	M	M	M
P_6	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
P_7	\X0F	\X0F	\X0F	\X0F	\X0F	\X0F	\X0F	\X0F	\X0F	\X0F	\X0F	\X0F	\X0F	\X0F	\X0F	\X0F

E_{key}: AES Encryption
$P_{0..7}$: Plaintext Blocks
$C_{0..7}$: Ciphertext Blocks

$$C_0 = E_k(IV \oplus P_0)$$
$$C_1 = E_k(C_0 \oplus P_1)$$
$$C_2 = E_k(C_1 \oplus P_2)$$
$$C_3 = E_k(C_2 \oplus P_3)$$
$$C_4 = E_k(C_3 \oplus P_4)$$
$$C_5 = E_k(C_4 \oplus P_5)$$
$$C_6 = E_k(C_5 \oplus P_6)$$
$$C_7 = E_k(C_6 \oplus P_7)$$

NOTE: Initialization Vector (IV) may be explicit or it may come from CBC residue depending on implementation version.

TLS CBC Mode Decryption

$C_0 = E_k(IV \oplus P_0)$	$P_0 = D_k(C_0) \oplus IV$
$C_1 = E_k(C_0 \oplus P_1)$	$P_1 = D_k(C_1) \oplus C_0$
$C_2 = E_k(C_1 \oplus P_2)$	$P_2 = D_k(C_2) \oplus C_1$
$C_3 = E_k(C_2 \oplus P_3)$	$P_3 = D_k(C_3) \oplus C_2$
$C_4 = E_k(C_3 \oplus P_4)$	$P_4 = D_k(C_4) \oplus C_3$
$C_5 = E_k(C_4 \oplus P_5)$	$P_5 = D_k(C_5) \oplus C_4$
$C_6 = E_k(C_5 \oplus P_6)$	$P_6 = D_k(C_6) \oplus C_5$
$C_7 = E_k(C_6 \oplus P_7)$	$P_7 = D_k(C_7) \oplus C_6$

This is called
MAC-Then-Pad-Then-Encrypt…

And It Is “Malleable”

CBC Malleability

Targeted Plaintext Manipulation

$$C_{n-1}^{'} = C_{n-1} \oplus X$$

$$P_{n}^{'} = P_{n} \oplus X$$

(And P_{n-1} is unpredictable)

Predicting Trouble

Vaudenay warned of “Padding Oracle” Attacks in 2002

No Change in TLSv1.1 (2006) and TLSv1.2 (2008)

What is a CBC Padding Oracle?

Attacker Learns Something About Plaintext			
Padding Validity	MAC Validity	Specific Bit Value	Plaintext Length

Padding Oracle Exploitation

Oracles may enable
Adaptive Chosen Ciphertext Attacks

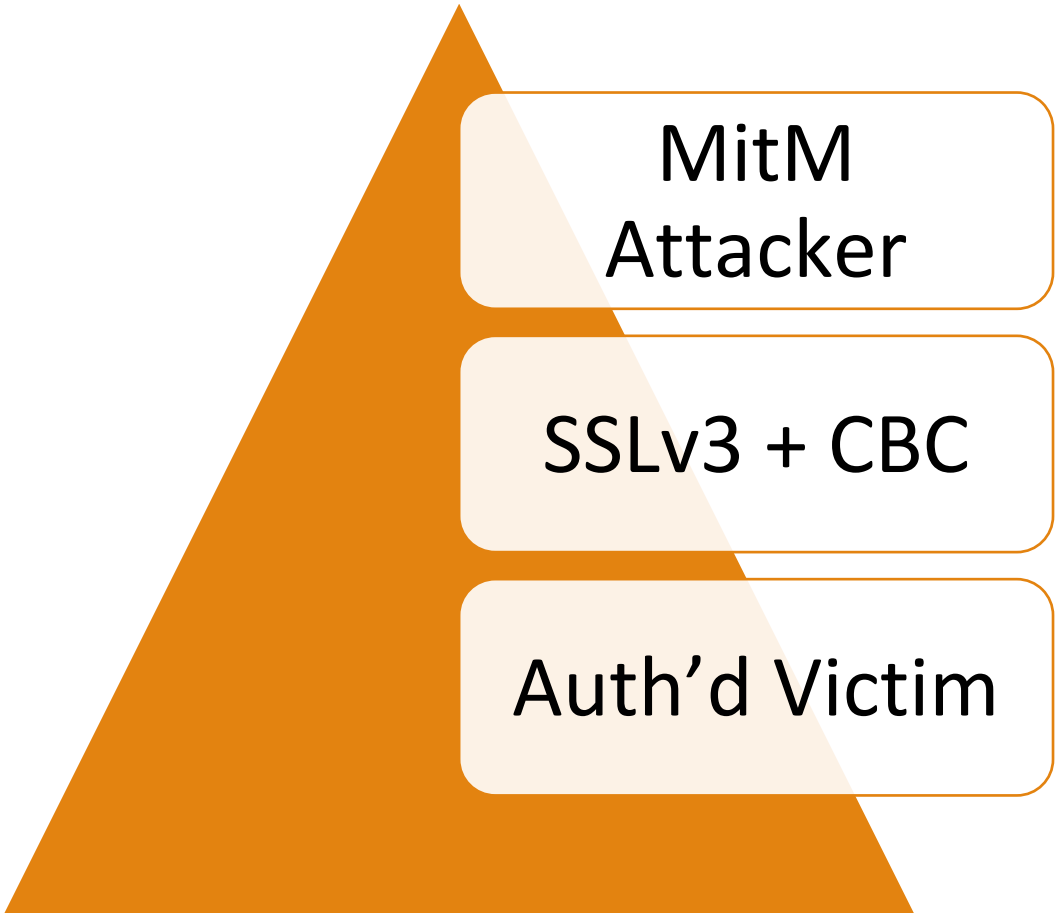
Oracle Observability

Attacker Must Be Able to Observe The Oracle

- Alerts may be encrypted
- Timing works, but is not practical

Observation via Wire or Browser

POODLE Case Study: Attack Requirements



POODLE Case Study: Exploitation Steps

Step 1: Downgrade to SSLv3

- Out of scope for this talk
- Google “TLS Fallback Dance”

POODLE Case Study: Exploitation Steps

Step 2: Generate Request

- JavaScript requests HTTPS from target
- Query has full block of padding

POODLE Case Study: Exploitation Steps

Step 3: Relocate Blocks

- Padding block replaced by block containing cookie
- Resulting record is sent to server

POODLE Case Study: Block Relocation Visualized

P_0	G	E	T		/	f	o	o	b	a	r		H	T	T	P
P_1	/	1	.	1	\X0D	\X0A	H	o	s	t	:		E	x	a	m
P_2	p	l	e	.	c	o	m	\x0D	\x0A	C	o	n	n	e	c	t
P_3	i	o	n	:		k	e	e	p	-	a	l	i	v	e	\x0D
P_4	\x0A	C	o	o	k	i	e	:		S	l	D	=	1	A	3
P_5	C	2	0	4	7	F	5	F	\X0D	\X0A	\X0D	\X0A	M	M	M	M
P_6	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
P_7	\X0F	\X0F	\X0F	\X0F	\X0F	\X0F	\X0F	\X0F	\X0F	\X0F	\X0F	\X0F	\X0F	\X0F	\X0F	\X0F

E_{key}: AES Encryption
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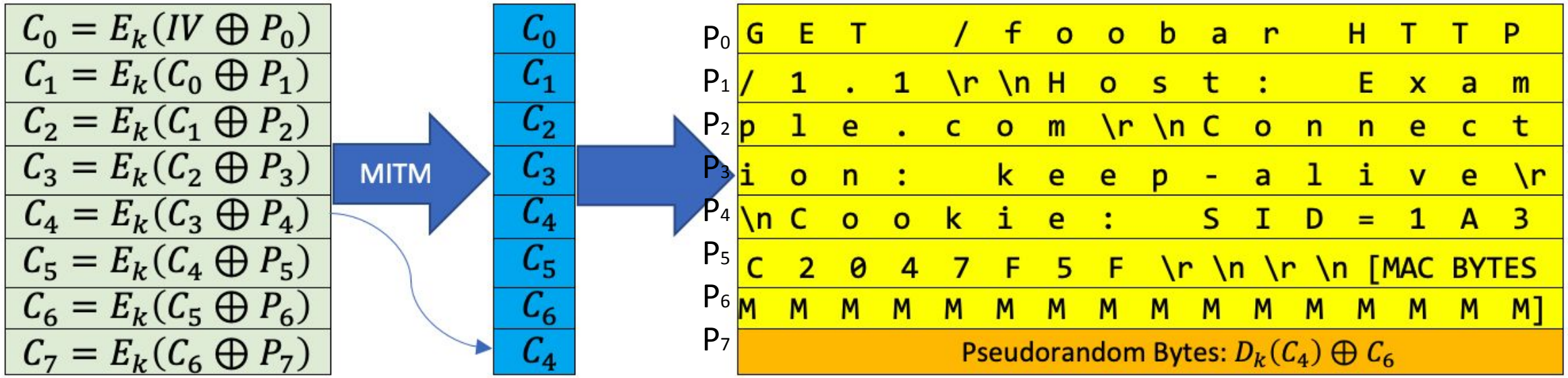
$C_3 = E_k(C_2 \oplus P_3)$
$C_4 = E_k(C_3 \oplus P_4)$
$C_5 = E_k(C_4 \oplus P_5)$
$C_6 = E_k(C_5 \oplus P_6)$
$C_7 = E_k(C_6 \oplus P_7)$

MITM

C_0 C_1 C_2 C_3 C_4 C_5 C_6 C_4

Server

POODLE Case Study: Server Decryption Visualized

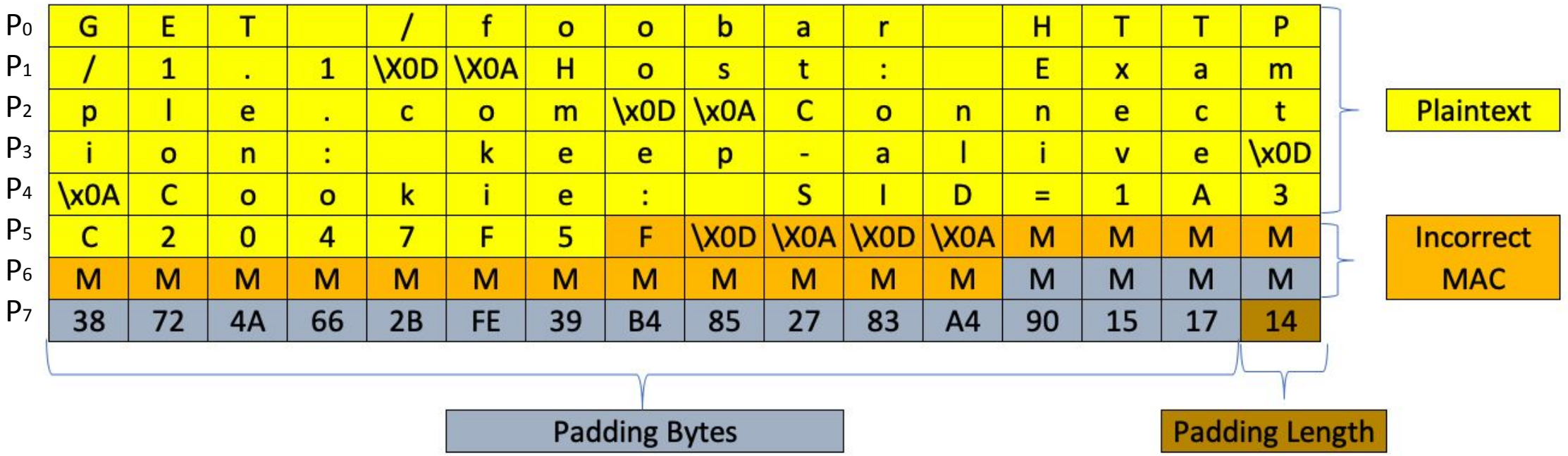


POODLE Case Study: Exploitation Steps

Step 4: Observe Oracle

- TLS Alert?
  - Back to Step 2
- No TLS Alert?
  - Onto Step 5

POODLE Case Study: Example Decryption Error



POODLE Case Study: Decryption Error Frequency

Most records trigger TLS alert

- About 1/256 decrypts will not error
- Think of a 256-side die landing on 15

POODLE Case Study: Successful Decryption Example

POODLE Case Study: Exploitation Steps

Step 5: Byte Decryption

POODLE Case Study: Exploitation Steps

Step 6: Adjust Request

- Put next byte of cookie as
- Return to step 2 until done

POODLE Case Study: Root Cause Analysis

Mac-Then-Pad-Then-Encrypt

- MAC does not include padding

SSLv3 Padding is Underspecified

- No way to recognize tampering

The POODLE Attack and TLS

TLS specifies padding bytes

No more POODLE, right?

POODLE Scanning

Researchers Made Tools To Scan For Similar Padding Oracles

POODLE TLS

Multiple vendors were using SSLv3 unpadding in TLS

POODLE TLS

POODLE Was Exploitable Again…

Patches To The Rescue!

All good now, right?

Maybe?

POODLE TLS Scanning

POODLE TLS is SSL Unpad Used in TLS

Test by Connecting With Invalid Client

- Scanner encrypts a badly padded Finished
- Vulnerable systems allow this connection

POODLE TLS Scanning Doesn’t Match Exploit

POODLE Doesn’t 'Bite' Finished

- Message is Forwarded Untouched

Research Questions

RQ1: Do stacks behave differently post-handshake?

RQ2: What other remote side-channels exist?

RQ3: How common are CBC oracles on the web?

Research Methodology

Build New Tool

Devise New Testcases

Scan Top Ranked Sites

Building a Tool

Based on Adam Langley's scanpad.go Example

- Uses patched Golang crypto/tls to break padding

Hacked it to only do bad padding for app data

Identifying New Signals

What Else Might Distinguish Error States?

- Received data quantity?
- TCP headers?

Distinction Must Be Observable

- Attacker must learn oracle response
- May observe via MitM or via JavaScript

Testcase Behavior

Complete Handshake

Send HTTP Request with Padding via Testcase

Observe/Record Response

- How many bytes?
- Socket aborted?

Scan Methodology

Responses from each test are compared

Differences considered possible vulns

Scan Reliability

Inconsistent Responses May Not Be Exploitable

Vulnerable Systems Should Get Triple Tested

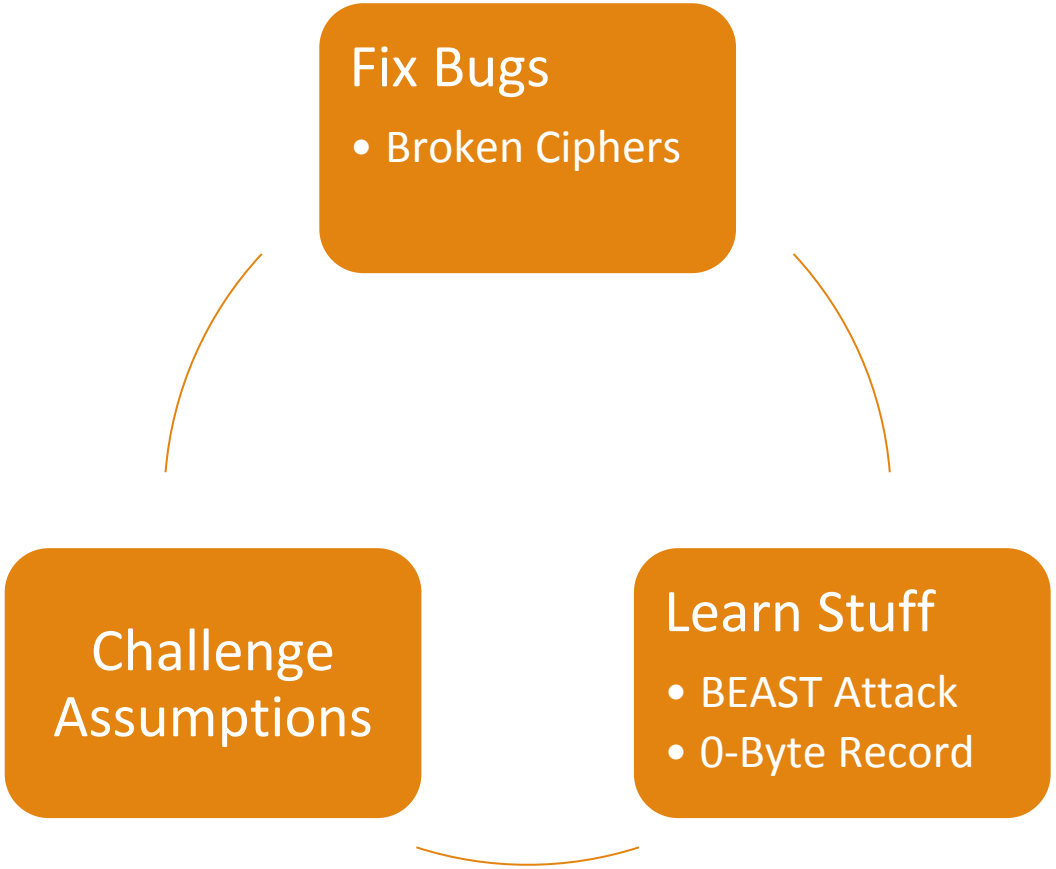
- Any variation will frustrate attacks

Initial Testcases (August 2018)

Each line represents the “padding block” of a malformed TLS record:

Test #1 - Valid Pad/Invalid MAC	\x00	\x01	\x02	\x03	\x04	\x05	\x06	\x07	\x08	\x09	\x0A	\x0B	\x0C	\x0D	\x0E	\x00
Test #2 - Incomplete Padding	\xFF	\xFF	\xFF	\xFF	\xFF	\xFF	\xFF	\xFF	\xFF	\xFF	\xFF	\xFF	\xFF	\xFF	\xFF	\xFF
Test #3 - Correct Length w/ Bad Values	\x10	\x0F	\x0E	\x0D	\x0C	\x0B	\x0A	\x09	\x08	\x07	\x06	\x05	\x04	\x03	\x02	\x0F
Test #4 - Pad Len is Plaintext Len	\x5F	\x5F	\x5F	\x5F	\x5F	\x5F	\x5F	\x5F	\x5F	\x5F	\x5F	\x5F	\x5F	\x5F	\x5F	\x5F
		Valid Pad				Invalid Pad				MAC Bytes				Pad Length		

Development Process



Current Testcases (March 11, 2019)

Each line represents the “padding block” of a malformed TLS record:

Test #1 - Valid Pad/Invalid MAC	\x00	\x01	\x02	\x03	\x04	\x05	\x06	\x07	\x08	\x09	\x0A	\x0B	\x0C	\x0D	\x0E	\x00
Test #2 - Incomplete Pad/No MAC	\xFF	\xFF	\xFF	\xFF	\xFF	\xFF	\xFF	\xFF	\xFF	\xFF	\xFF	\xFF	\xFF	\xFF	\xFF	\xFF
Test #3 - Invalid Pad/Valid MAC	\x10	\x0F	\x0E	\x0D	\x0C	\x0B	\x0A	\x09	\x08	\x07	\x06	\x05	\x04	\x03	\x02	\x0F
Test #4 - Valid Pad/No MAC	\x5F	\x5F	\x5F	\x5F	\x5F	\x5F	\x5F	\x5F	\x5F	\x5F	\x5F	\x5F	\x5F	\x5F	\x5F	\x5F
Test #5 - 0-Length Record*	\x0F	\x0F	\x0F	\x0F	\x0F	\x0F	\x0F	\x0F	\x0F	\x0F	\x0F	\x0F	\x0F	\x0F	\x0F	\x0F

*CVE-2019-1559 found by Somorovsky, Merget, and Aviram

Valid Pad | Invalid Pad | MAC Bytes | Pad Length

Testcase 1: Valid Padding, Invalid MAC

\x00	\x01	\x02	\x03	\x04	\x05	\x06	\x07	\x08	\x09	\x0A	\x0B	\x0C	\x0D	\x0E	\x00

Zero-length padding is represented by a single null byte.

Testcase 2: Invalid Padding, Not Enough Record

Padding length 255 exceeds record length.

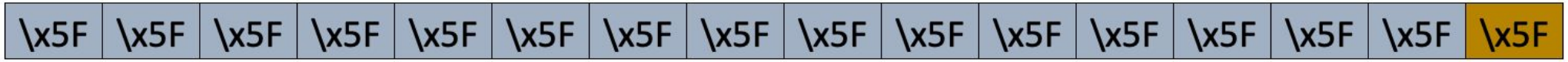
NOTE: As of March, plaintext is also \xFF bytes for valid (incomplete) padding.

Testcase 3: Invalid Padding, Valid MAC (POODLE)

\x10	\x0F	\x0E	\x0D	\x0C	\x0B	\x0A	\x09	\x08	\x07	\x06	\x05	\x04	\x03	\x02	\x0F

Padding bytes are non-deterministic.

Testcase 4: Invalid Padding, Missing MAC



Padding length is record length

NOTE: As of March, this is 6 blocks of bytes with value (6*blockSize-1).

Testcase 5: 0-Length Record (Added in March)

Padding length is record length minus MAC length.

(This record would also have 2 blocks for a 32 byte SHA256 MAC.)

This can trigger CVE-2019-1559 as found by Juraj Somorovsky, Robert Merget, and Nimrod Aviram
More info @ https://github.com/RUB-NDS/TLS-Padding-Oracles

Scanning Tripwire's Lab For Calibration

Detected expected POODLE TLS targets

- Compared against IP360 detection results

Detected a non-POODLE target too

- Cisco ASA with CVE-2015-4458

Cisco ASA CVE-2015-4458

MAC Validation Failure Due to Cavium Bug

- Yngve Pettersen found this with TLS Prober

"MAC Error" (MACE) Vulnerability

- Detailed on, "The POODLE has friends" blog post: https://yngve.vivaldi.net/2015/07/14/the-poodle-has-friends/

Cisco ASA CVE-2015-4458

Bug is actually a classic padding oracle

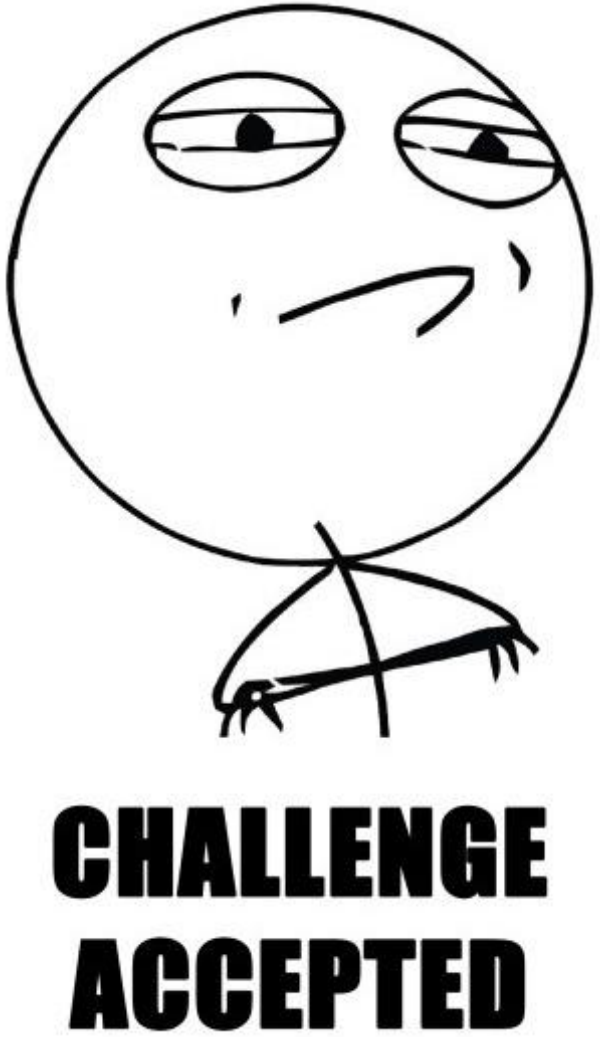
CVE-2015-4458: MITRE's Description

The TLS implementation in the Cavium cryptographic-module firmware, as distributed with Cisco Adaptive Security Appliance (ASA) Software 9.1(5.21) and other products, does not verify the MAC field, which allows man-in-the-middle attackers to **spoof TLS content** by modifying packets, aka Bug ID CSCuu52976.

Cisco Advisory: https://tools.cisco.com/security/center/viewAlert.x?alertId=39919

A successful exploit of this vulnerability **does not allow an attacker to decrypt** the packets in transit or obtain information about the session keys being used for the TLS connection.

Can’t Decrypt Packets?



Meet POODLE's Friend GOLDENDOODLE

Same attack scenario as POODLE

- MitM + CBC Ciphers

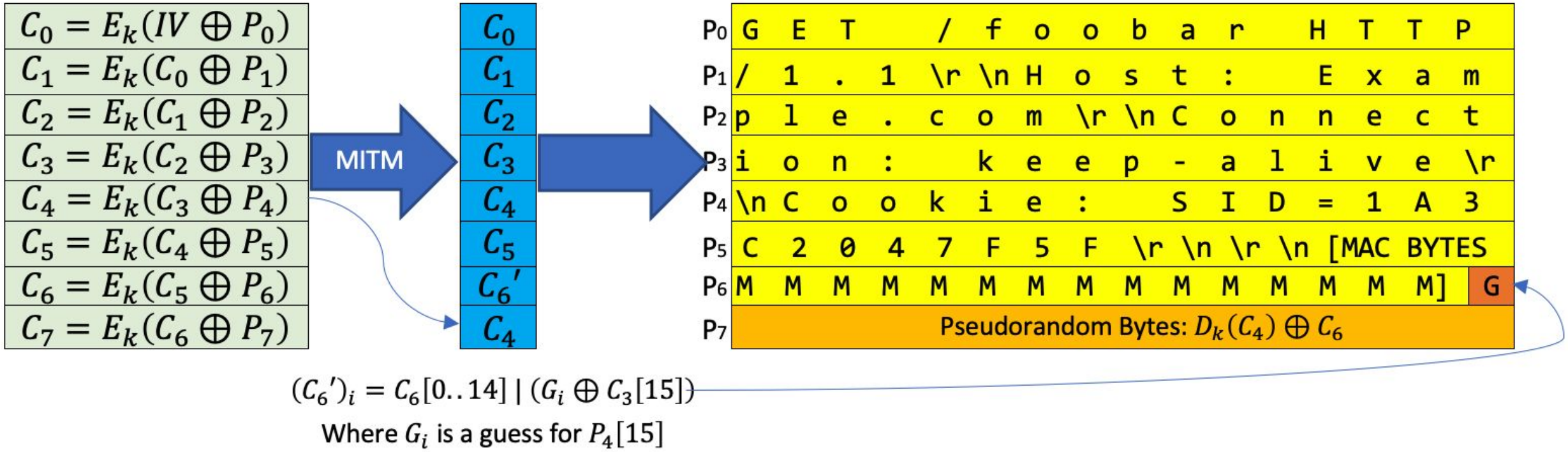
Same impact as POODLE

- Decryption of authentication headers/cookies

Much faster than POODLE

- Decryption is deterministic

Example GOLDENDOODLE Transform



Example GOLDENDOODLE Transform

If $G_i = P_4[15]$ then $C_7[15] = 0$

P_0	G	E	T		/	f	o	o	b	a	r		H	T	T	P
P_1	/	1	.	1	\X0D	\X0A	H	o	s	t	:		E	x	a	m
P_2	p	l	e	.	c	o	m	\x0D	\x0A	C	o	n	n	e	c	t
P_3	i	o	n	:		k	e	e	p	-	a	l	i	v	e	\x0D
P_4	\x0A	C	o	o	k	i	e	:		S	l	D	=	1	A	3
P_5	C	2	0	4	7	F	5	F	\X0D	\X0A	\X0D	\X0A	M	M	M	M
P_6	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	G
P_7	38	72	4A	66	2B	FE	39	B4	85	27	83	A4	90	15	17	\x00

Plaintext

Invalid MAC

No Padding Bytes

Padding Length

GOLDENDOODLE Performance

Attack can guess 1 byte with each intercepted request

Any byte can be decrypted with at most 255 requests

- POODLE requires an **average** of 256 requests/byte

HTTP headers use a limited ASCII character set

- Max 94 requests for any printable character
- Max 15 requests for any fixed case hexadecimal

GOLDENDOODLE Proof-of-Concept

Quick PoC Completed in a Day

- Used Python + iptables
- cURL in a loop as “victim”
- Tested with SSL-VPN on ASA 9.1(6)

Next Finding: "Zombie POODLE"

Not POODLE TLS -- But Similar

Mishandling Application Data Records with SSLv3 Style Pad

- Most commonly an extra TLS alert only on testcase #3

Exploited with POODLE algorithm almost verbatim

- Oracle is basically just inverted from POODLE
- TLS alert means good padding length in Zombie POODLE

Scanning the Internet

Alexa Top 1M

Includes Most Popular Stacks

~85% Supports SSL/TLS

Used for ROBOT scans

Findings (August-December 2018 Combined Results)

At least 100 discernible behaviors

- Most are observed on only 1 or 2 hosts
- 46 were observed on at least 10 domains each

Over 5800 domains are readily exploitable

- Only counting hosts with consistent and observable oracles
- Under 1000 with POODLE TLS behavior
- About 1000 can be exploited via GOLDENDOODLE
- The rest can be exploited via “Zombie POODLE”

March 2019 Findings (After 3 Public Advisories)

129 discernible behaviors

- Used second Read() and Close() error returns for more signals
- Fixed broken ciphersuites
- Testing with multiple blocks

7,947 domains with oracles (March 11-12, 2019)

- 3,689 marked as ‘Observable’

Impact

Around 1.6% of the TLS enabled Alexa top 100K

- Nearly 1% out of all Alexa ranked sites with TLS
- Scans conducted March 11-12, 2018

Many high-profile sites

- Financial
- Government
- Commerce

Caveats/Limitations

Far more hosts are vulnerable

- Some oracles are cipher/protocol specific
- Padcheck tests only the preferred CBC cipher/protocol
- More test cases are possible

Sleeping POODLE?

Some Hosts Only Look Like POODLE TLS

- Servers reject malformed Finished
- Tested tools did not report a padding oracle

App Records Handled Differently

- Padding check on Finished, but not on Application Record

Disclosures

Citrix (CVE-2019-6485)

- Mostly Zombie POODLE and Some GOLDENDOODLE

F5 (CVE-2019-6593)

- Mostly GOLDENDOODLE but also Zombie POODLE

Four More Vendors Identified for Disclosure

- Load Balancer / Firewall / VPN / IPS

Missed Opportunities

Possibly Important Things That Aren't Top Ranked Sites

- Browser Based VPN
- Devices Found Only on LANs

More Subtle Padding Oracles

- No Individual MAC Byte Checks

TLS 1.3 To Save Us All?

No More CBC in TLS 1.3!

Moving Forward

STOP using TLS CBC ciphers

START using TLS 1.3

Acknowledgements

Hanno Böck

- Inspired me to investigate CBC padding oracles

Robert Merget, Juraj Somorovsky, and Nimrod Aviram

- Developed a far more extensive padding oracle test tool
- Provided guidance on testing and exploitation methodology

Thanks!

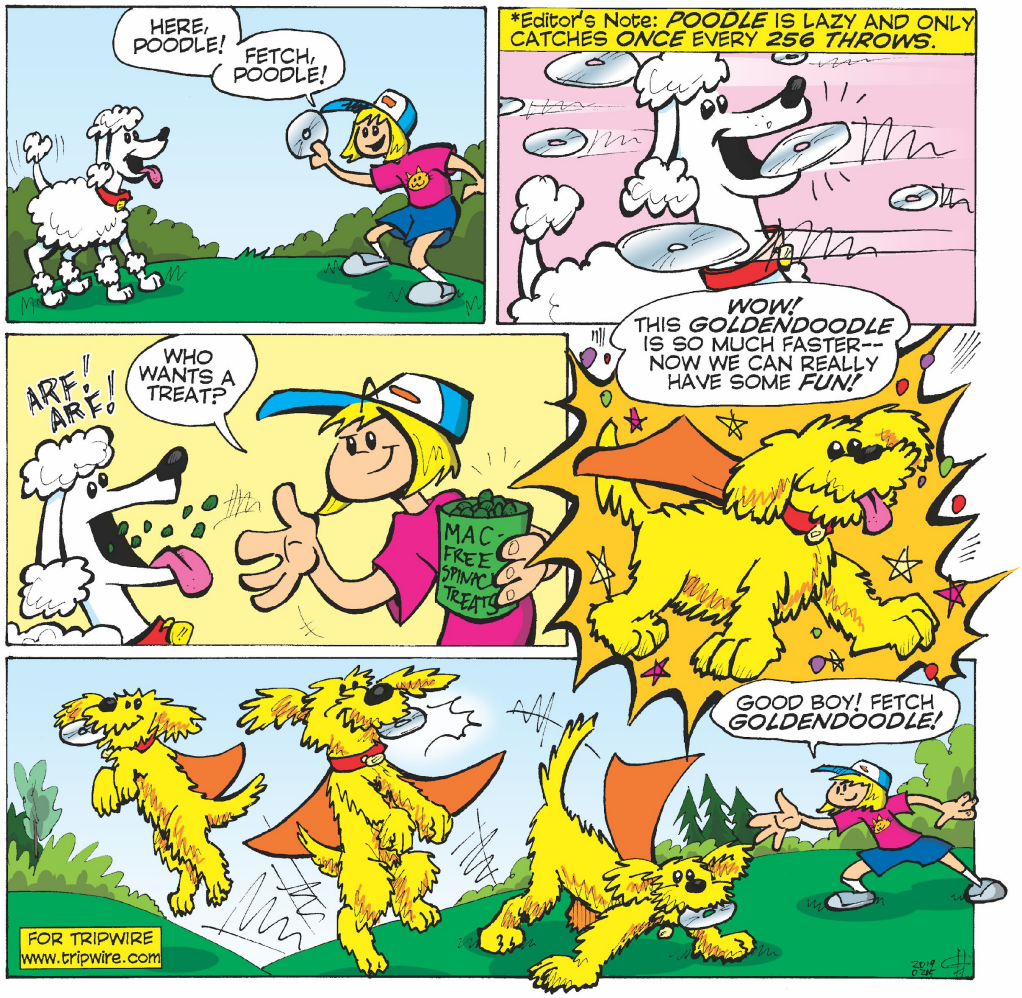
Padcheck Scanner Repo

- https://github.com/Tripwire/padcheck

Ruhr University Repo Tracks Vulns

- https://github.com/RUB-NDS/TLS-Padding-Oracles

Questions?


HERE, POODLE!
FETCH, POODLE!
*Editor's Note: POODLE IS LAZY AND ONLY CATCHES ONCE EVERY 256 THROWS.
WOW! THIS GOLDENDOODLE IS SO MUCH FASTER-- NOW WE CAN REALLY HAVE SOME FUN!
ARF! ARF!
WHO WANTS A TREAT?
MAC FREE SPINAC TREATS
GOOD BOY! FETCH GOLDENDOODLE!
FOR TRIPWIRE www.tripwire.com


IS IT DONE?
YES. POODLE IS NO MORE.
BUMP!
FOR TRIPWIRE www.tripwire.com
I'VE DONE IT! A FEW SMALL CHANGES AND THE POODLE IS RESURRECTED AS THE ZOMBIE POODLE!