Network Security (NetSec)

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Chapter 11: Secure Channel

Secure Channel

MAC-then-Enc vs. Enc-then-MAC

Secure Channel Implementation

Secure Channel (ESP) in the OpenBSD Kernel

Authenticated Encryption With Associated Data

Attacks against a Secure Channel (Stream Cipher)

Attacks against a Secure Channel (Padding oracle)

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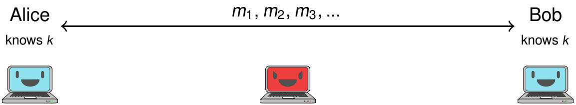
Secure Channel



What do we want?

- Confidentiality, Integrity, Authenticity
- Messages received in correct order
- No duplicates and we know which messages are missing

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MAC-then-Enc vs. Enc-then-MAC

$$\mathrm{Enc}_{k\text{-}enc}(m, \mathrm{MAC}_{k\text{-}int}(m))$$

vs.

$$\mathrm{Enc}_{k\text{-}enc}(m), \mathrm{MAC}_{k\text{-}int}(m)$$

vs.

$$\mathrm{Enc}_{k\text{-}enc}(m), \mathrm{MAC}_{k\text{-}int}(\mathrm{Enc}_{k\text{-}enc}(m))$$

MAC-then-Enc vs. Enc-then-MAC

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vs. $\mathrm{Enc}_{k\text{-}enc}(\mathrm{MAC}_{k\text{-}int}(m))$

MAC-then-Enc vs. Enc-then-MAC

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vs. $\cancel{\mathsf{Enc}_{k\text{-}enc}(\mathsf{MAC}_{k\text{-}int}(m))}$

- Cannot recover m

MAC-then-Enc vs. Enc-then-MAC

- $\text{Enc}_{k\text{-}enc}(m, \text{MAC}_{k\text{-}int}(m))$:
  - "*The encryption protects the MAC*"

MAC-then-Enc vs. Enc-then-MAC

- $\text{Enc}_{k\text{-}enc}(m, \text{MAC}_{k\text{-}int}(m))$:
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    - Encryption does not provide any message authenticity/integrity!

MAC-then-Enc vs. Enc-then-MAC

- $\text{Enc}_{k\text{-}enc}(m, \text{MAC}_{k\text{-}int}(m))$:
  - ~~“*The encryption protects the MAC*”~~
    - Encryption does not provide any message authenticity/integrity!
  - Example: A weak MAC cannot be “protected” by encrypting it
  - CRC is not a MAC, OTP is perfect encryption
  - $\text{OTP}_k(m, \text{CRC}(m))$ does not provide any integrity

MAC-then-Enc vs. Enc-then-MAC

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  - ~~“*The encryption protects the MAC*”~~
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  - Example: A weak MAC cannot be “protected” by encrypting it
  - CRC is not a MAC, OTP is perfect encryption
  - $\text{OTP}_k(m, \text{CRC}(m))$ does not provide any integrity
  - Attacker can $\oplus x$ to encrypted message and $\oplus\text{CRC}(x)$ to the encrypted CRC to fix it

MAC-then-Enc vs. Enc-then-MAC

- $\text{Enc}_{k\text{-}enc}(m, \text{MAC}_{k\text{-}int}(m))$:
  - Horton principle:“*Authenticate what you mean, not what you say*”
  - “*Authenticate the plaintext!*”

MAC-then-Enc vs. Enc-then-MAC

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    - Do you really mean `char *`?

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- Horton principle applies to application layer

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- Horton principle applies to application layer
- E.g., Signing a contract

http://www.personalausweisportal.de/DE/Buergerinnen-und-Buerger/Online-Ausweisen/Das-brauche-ich/Kartenlesegeraete/Kartenlesegeraete_node.html

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- E.g., Signing a contract
- The secure channel transports chunks of bytes

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- Horton principle applies to application layer
- E.g., Signing a contract
- The secure channel transports chunks of bytes out of context
- m_1 = `"<!--"`,
  m_2 = `"I owe you $1000"`,
  m_3 = `"-->"`

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MAC-then-Enc vs. Enc-then-MAC

- $\mathrm{Enc}_{k\text{-}enc}(m)$, $\mathrm{MAC}_{k\text{-}int}(m)$:
  - Not better than $\mathrm{Enc}_{k\text{-}enc}(m, \mathrm{MAC}_{k\text{-}int}(m))$

MAC-then-Enc vs. Enc-then-MAC

- $\mathsf{Enc}_{\textit{k-enc}}(m), \mathsf{MAC}_{\textit{k-int}}(\mathsf{Enc}_{\textit{k-enc}}(m))$:
  - $c \leftarrow \mathsf{Enc}_{\textit{k-enc}}(m)$, $\mathsf{MAC}_{\textit{k-int}}(c)$

MAC-then-Enc vs. Enc-then-MAC

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  - $c \leftarrow \text{Enc}_{k\text{-}enc}(m), \text{MAC}_{k\text{-}int}(c)$
  - Considered secure

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  - Discard bogus messages before decryption

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  - Discard bogus messages before decryption
    - Don't waste CPU power

MAC-then-Enc vs. Enc-then-MAC

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  - Discard bogus messages before decryption
    - Don't waste CPU power
    - Don't generate error messages that might help an attacker

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  - $c \leftarrow \text{Enc}_{k\text{-}enc}(m), \text{MAC}_{k\text{-}int}(c)$
  - Considered secure
  - Discard bogus messages before decryption
    - Don't waste CPU power
    - Don't generate error messages that might help an attacker
    - Don't touch non-authentic data!

MAC-then-Enc vs. Enc-then-MAC
Examples

- $\text{Enc}_{k\text{-}enc}(m, \text{MAC}_{k\text{-}int}(m))$
  - MAC then encrypt
  - SSL ← many SSL attacks are a result of this scheme
  - Horton Principle
- $\text{Enc}_{k\text{-}enc}(m), \text{MAC}_{k\text{-}int}(m)$
  - MAC & encrypt
  - SSH
  - Horton Principle
  - Considered the weakest
- $\text{Enc}_{k\text{-}enc}(m), \text{MAC}_{k\text{-}int}(\text{Enc}_{k\text{-}enc}(m))$
  - Encrypt then MAC
  - IPSec (ESP), Signal (TextSecure ProtovolV2), probably TLS 1.3 [RCF7366]
  - Considered the most secure

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Secure Channel Implementation

- Our Secure Channel Implementation:
  - We need
    - Message numbering
    - Authentication
    - Encryption
  - Our Toy Implementation
    - Message numbering: n (next slide)
    - Authentication: HMAC-SHA-256

      $\text{MAC}_{k\text{-}int}(n \mid\mid IV \mid\mid c)$
    - Encryption: AES-128-CTR

      $c \leftarrow \text{ENC}_{k\text{-}enc}(IV, m)$
    - keys for each purpose

Secure Channel Implementation

- Message Numbering:
  - $n \in \mathbb{N}$
  - Increased monotonically for each valid message
  - n must be unique for every message
  - Remember last message n_{last} and only accept $n > n_{last}$

Secure Channel Implementation

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  - Detect replays
  - Correct order
  - Detect lost messages

Secure Channel Implementation

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  - $n \in \mathbb{N}$
  - Increased monotonically for each valid message
  - n must be unique for every message
  - Remember last message n_{last} and only accept $n > n_{last}$

  - Detect replays
  - Correct order
  - Detect lost messages

  - Number overflow $\rightarrow$ rekeying

Secure Channel Implementation

- Initialize (at Alice):

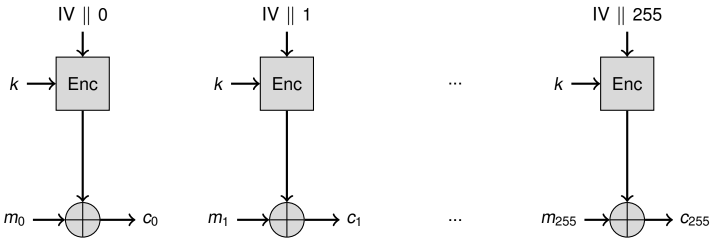
```
# Output: 128bit key
def KDF(k):
    # TODO: There are better key derivation functions
    # Assumes: random oracle property of SHA1
    return SHA1(k)

# Initialize global variables (keys and message number)
def init_globals(k):
    global K_send_enc, K_recv_enc, K_send_int, K_recv_int, n_send, n_recv, used_nonces
    K_send_enc = KDF(k || "Enc Alice to Bob")
    K_recv_enc = KDF(k || "Enc Bob to Alice")
    K_send_int = KDF(k || "MAC Alice to Bob")
    K_recv_int = KDF(k || "MAC Bob to Alice")
    n_send = 1
    n_recv = 0
    used_nonces = {}
```

- Generate one key for each purpose
- Where $\cdot \parallel \cdot$ means string/byte concatenation

Secure Channel Implementation

- AES-128-CTR Mode needs IV:
  - ctr_i = IV $\|$ i
  - ctr_i is of length 128 bit: We chose 120 bit IV and 8 bit i



- Max message size per IV: $2^8 \cdot 128 = 32768$ bit = 4096 Bytes
- For $i \in \{0 \dots 254\}$: $ctr_{i+1} = ctr_i + 1$

Secure Channel Implementation

- Nonces as IV for AES-CTR:

```
used_nonces = {}

# Output: A fresh 120bit nonce
def nonce():
    global used_nonces
    n = random_bits(120)
    if n not in used_nonces:
        used_nonces.add(n)
        return n
    else:
        # TODO: may not terminate if no unused nonces are left
        return nonce()
```

- We want a fresh IV $\rightarrow$ remember used nonces
- We are super paranoid:
  - Random nonces
  - A counter would suffice

Secure Channel Implementation

- Sending a Message:

```
def send(m):
    global n_send, K_send_enc, K_send_int
    if n_send >= MAX_INT:
        return ERROR("MSG Number overflow, needs rekeying")

    if len(m) > 4096:
            return ERROR("MSG too large, needs fragmentation")

    IV = nonce()

    c = ENC-AES-128-CTR(K_send_enc, IV, m)

    t = HMAC-SHA-256(K_send_int, n_send || IV || c)

    socket_send(n_send || IV || c || t)

    n_send = n_send + 1
```

Secure Channel Implementation

- Verifying a MAC:

```
def verify(k, msg, t):
    return HMAC-SHA-256(k, msg) == t
```

Secure Channel Implementation

- Verifying a MAC correctly:

```
def verify(k, msg, t):
    return timingsafe_bcmp(HMAC-SHA-256(k, msg), t, 32)
```

OpenBSD/sys/lib/libkern/timingsafe_bcmp.c

```
int timingsafe_bcmp(const void *b1, const void *b2, size_t n)
{
    const unsigned char *p1 = b1, *p2 = b2;
    int ret = 0;

    for (; n > 0; n--)
        ret |= *p1++ ^ *p2++;
    return (ret != 0);
}
```

The timingsafe_bcmp() and timingsafe_memcmp() functions lexicographically compare the first len bytes (each interpreted as an unsigned char) pointed to by b1 and b2. Additionally, their running times are independent of the byte sequences compared, making them safe to use for comparing secret values such as cryptographic MACs. In contrast, bcmp(3) and memcmp(3) may short-circuit after finding the first differing byte.

Secure Channel Implementation

- Receiving a Message:

```
def receive(msg):
    global n_recv, K_recv_int, K_recv_enc
    if n_recv + 1 >= MAX_INT:
        return ERROR("MSG Number overflow, need rekeying")

    n, IV, c, t = parse(msg)

    if not verify(K_recv_int, n || IV || c, t):
        return ERROR("MAC verification failed")

    if n <= n_recv:
        return ERROR("Received old message")

    if n != n_recv + 1:
         print "lost %d messages" % (n - (n_recv + 1))

    n_recv = n

    m = DEC-AES-128-CTR(K_recv_enc, IV, c)

    return m
```

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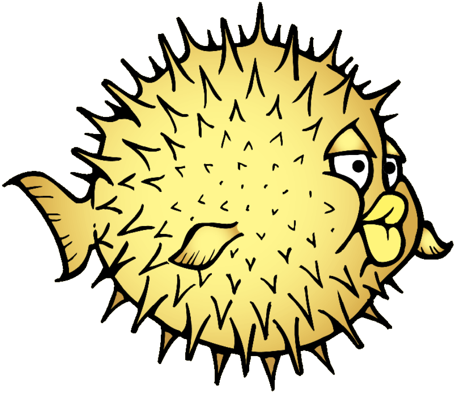
IPSec ESP in the OpenBSD Kernel



Secure Channel (ESP) in the OpenBSD Kernel

- ESP Input Processing:
  `sys/netinet/ip_esp.c` OpenBSD 5.8

```
/*
 * ESP input processing, called (eventually) through the protocol switch.
 */
int
esp_input(struct mbuf *m, struct tdb *tdb, int skip, int protoff)
{
    struct auth_hash *esph = (struct auth_hash *) tdb->tdb_authalgxform;
    struct enc_xform *espx = (struct enc_xform *) tdb->tdb_encalgxform;
    struct cryptodesc *crde = NULL, *crda = NULL;
    struct cryptop *crp;
    struct tdb_crypto *tc;
    int plen, alen, hlen;
    u_int32_t btsx, esn;

    /* Determine the ESP header length */
    hlen = 2 * sizeof(u_int32_t) + tdb->tdb_ivlen; /* "new" ESP */
    alen = esph ? esph->authsize : 0;
    plen = m->m_pkthdr.len - (skip + hlen + alen);
    if (plen <= 0) {
        DPRINTF(("esp_input: invalid payload length\n"));
        espstat.esps_badilen++;
        m_freem(m);
        return EINVAL;
    }
```

- Both encryption and authentication are optional in ESP

Secure Channel (ESP) in the OpenBSD Kernel

```
if (espx) {
    /*
     * Verify payload length is multiple of encryption algorithm
     * block size.
     */
    if (plen & (espx->blocksize - 1)) {
        DPRINTF(("esp_input(): payload of %d octets "
            "not a multiple of %d octets, SA %s/%08x\n",
            plen, espx->blocksize, ipsp_address(&tdb->tdb_dst,
            buf, sizeof(buf)), ntohl(tdb->tdb_spi)));
        espstat.esps_badilen++;
        m_freem(m);
        return EINVAL;
    }
}
```

- if encryption is to be applied

```c
/* Replay window checking, if appropriate -- no value commitment. */
if (tdb->tdb_wnd > 0) {
    m_copydata(m, skip + sizeof(u_int32_t), sizeof(u_int32_t), (unsigned char *) &btsx);
    btsx = ntohl(btsx);

    switch (checkreplaywindow(tdb, btsx, &esn, 0)) {
    case 0: /* All's well */
        break;
    case 1:
        m_freem(m);
        DPRINTF(("esp_input(): replay counter wrapped for SA %s/%08x\n",
            ipsp_address(&tdb->tdb_dst, buf, sizeof(buf)), ntohl(tdb->tdb_spi)));
        espstat.esps_wrap++;
        return EACCES;
    case 2:
        m_freem(m);
        DPRINTF(("esp_input(): old packet received in SA %s/%08x\n",
            ipsp_address(&tdb->tdb_dst, buf, sizeof(buf)), ntohl(tdb->tdb_spi)));
        espstat.esps_replay++;
        return EACCES;
    case 3:
        m_freem(m);
        DPRINTF(("esp_input(): duplicate packet received in SA %s/%08x\n",
            ipsp_address(&tdb->tdb_dst, buf, sizeof(buf)), ntohl(tdb->tdb_spi)));
        espstat.esps_replay++;
        return EACCES;
    default:
        m_freem(m);
        DPRINTF(("esp_input(): bogus value from checkreplaywindow() in SA %s/%08x\n",
            ipsp_address(&tdb->tdb_dst, buf, sizeof(buf)), ntohl(tdb->tdb_spi)));
        espstat.esps_replay++;
        return EACCES;
    }
}
```

`int checkreplaywindow(struct tdb *tdb, u_int32_t seq, u_int32_t *seqh, int commit)` i.e. do not update replay window

```
    /* Update the counters */
    tdb->tdb_cur_bytes += m->m_pkthdr.len - skip - hlen - alen;
    espstat.esps_ibytes += m->m_pkthdr.len - skip - hlen - alen;

    /* Hard expiration */
    if ((tdb->tdb_flags & TDBF_BYTES) &&
        (tdb->tdb_cur_bytes >= tdb->tdb_exp_bytes))    {
        pfkeyv2_expire(tdb, SADB_EXT_LIFETIME_HARD);
        tdb_delete(tdb);
        m_freem(m);
        return ENXIO;
    }

    /* Notify on soft expiration */
    if ((tdb->tdb_flags & TDBF_SOFT_BYTES) &&
        (tdb->tdb_cur_bytes >= tdb->tdb_soft_bytes)) {
        pfkeyv2_expire(tdb, SADB_EXT_LIFETIME_SOFT);
        tdb->tdb_flags &= ~TDBF_SOFT_BYTES;       /* Turn off checking */
    }

    /* Get crypto descriptors */
    crp = crypto_getreq(esph && espx ? 2 : 1);
    if (crp == NULL) {
        m_freem(m);
        DPRINTF(("esp_input(): failed to acquire crypto descriptors\n"));
        espstat.esps_crypto++;
        return ENOBUFS;
    }

...
```

- Keys may expire after certain number of bytes
- Note: packet might still be bogus, replay window not updated

```
    if (esph) {
        crda = crp->crp_desc;
        crde = crda->crd_next;

        /* Authentication descriptor */
        crda->crd_skip = skip;
        crda->crd_inject = m->m_pkthdr.len - alen;

        crda->crd_alg = esph->type;
        crda->crd_key = tdb->tdb_amxkey;
        crda->crd_klen = tdb->tdb_amxkeylen * 8;

        if ((tdb->tdb_wnd > 0) && (tdb->tdb_flags & TDBF_ESN)) {
            esn = htonl(esn);
            bcopy(&esn, crda->crd_esn, 4);
            crda->crd_flags |= CRD_F_ESN;
        }

        if (espx && espx->type == CRYPTO_AES_GCM_16)
            crda->crd_len = hlen - tdb->tdb_ivlen;
        else
            crda->crd_len = m->m_pkthdr.len - (skip + alen);

        /* Copy the authenticator */
        m_copydata(m, m->m_pkthdr.len - alen, alen, (caddr_t)(tc + 1));
    } else
        crde = crp->crp_desc;

    /* Crypto operation descriptor */
...
```

- if authentication is to be applied

Secure Channel (ESP) in the OpenBSD Kernel

```
/* Decryption descriptor */
if (espx) {
    crde->crd_skip = skip + hlen;
    crde->crd_inject = skip + hlen - tdb->tdb_ivlen;
    crde->crd_alg = espx->type;
    crde->crd_key = tdb->tdb_emxkey;
    crde->crd_klen = tdb->tdb_emxkeylen * 8;
    /* XXX Rounds ? */

    if (crde->crd_alg == CRYPTO_AES_GMAC)
        crde->crd_len = 0;
    else
        crde->crd_len = m->m_pkthdr.len - (skip + hlen + alen);
}
```

- if encryption is to be applied

Secure Channel (ESP) in the OpenBSD Kernel

```
    return crypto_dispatch(crp);
}
```

- Dispatch to crypto driver (similar to Linux)
- A callback will be called once the crypto was done

```c
/*
 * ESP input callback, called directly by the crypto driver.
 */
int
esp_input_cb(struct cryptop *crp)
{
...
    /* If authentication was performed, check now. */
    if (esph != NULL) {
...
        /* Verify authenticator */
        if (timingsafe_bcmp(ptr, aalg, esph->authsize)) {
            free(tc, M_XDATA, 0);
            DPRINTF(("esp_input_cb(): authentication failed for packet in SA %s/%08x\n",
                ipsp_address(&tdb->tdb_dst, buf, sizeof(buf)), ntohl(tdb->tdb_spi)));
            espstat.esps_badauth++;
            error = EACCES;
            goto baddone;
        }

        /* Remove trailing authenticator */
        m_adj(m, -(esph->authsize));
    }
    free(tc, M_XDATA, 0);

    /* Replay window checking, if appropriate */
...
    /* Verify pad length */
...
    /* Verify correct decryption by checking the last padding bytes */
...
}
```

- Check if everything was correct (in the right order)
- update replay window

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Authenticated Encryption With Associated Data

- Authenticated Encryption With Associated Data (AEAD):
  - Authenticated encryption: Encrypt then MAC
  - Associated Data: Additional non-encrypted data but authenticated
  - Example AD: IV, information necessary for message routing, . . .
  - Special AEAD Algorithms: only need one pass over the data
    - Encrypt and MAC usually requires two passes
  - Examples
    - Offset Codebook Mode (OCB)
    - Galois/Counter Mode (GCM)

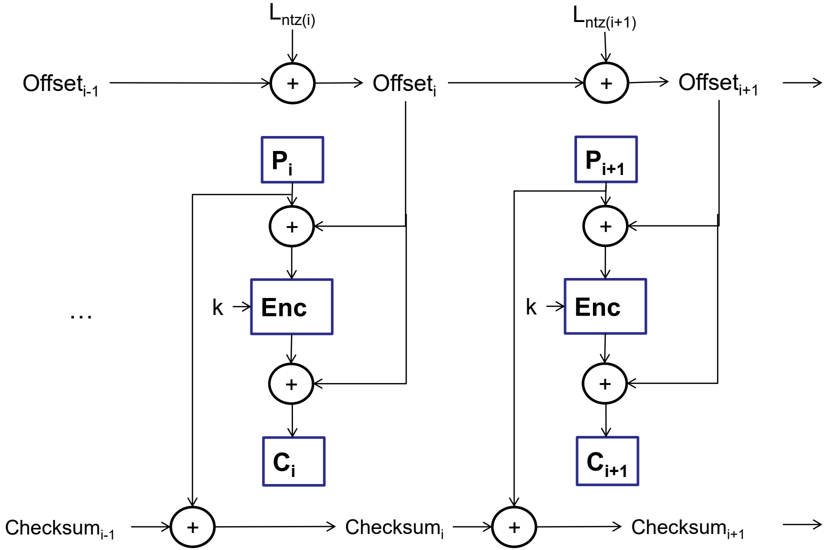
Offset Codebook Mode (OCB)

- Offset Codebook Mode
  - Authenticated Encryption Mode
  - Proposed 2001 [OCB1]
  - Standardized May 2014 [RFC 7253]
  - Encryption
    - Inspired by ECB with block-dependent offsets (avoids ECB problems!)
  - Associated Data *A*
    - *A* is not encrypted but authenticated
    - For example: Unencrypted header data
  - MAC
    - Checksum = XOR over plaintext, length- and key-dependent variables
    - MAC = (Encryption of checksum with shared key k) XOR (hash(k,A))
  - Requires only one key K for encryption and authentication
  - Requires a fresh nonce every time

Offset Codebook Mode (OCB)

- Let double be multiplication by the variable in the OCB Galois Filed
- Variables depending on the key: $L_\star, L_\$, L_0, L_1, L_2, ...$
  - $L_\star = Enc_K(0)$
  - $L_\$ = \text{double}(L_\star)$
  - $L_0 = \text{double}(L_\$)$
  - $L_i = \text{double}(L_{i-1})$
- Let *ntz* be number of trailing zeros (zero bits at the end)
- Usage of the L's
  - $L_\$ \rightarrow$ MAC
  - $L_\star \rightarrow$ last block
  - $L_{ntz(i)} \rightarrow$ intermediate blocks
- Note: $L_{ntz(i)}$ is used
  - Only few L_i are needed (for a fixed K)
  - They can be pre-computed and stored in a Lookup table

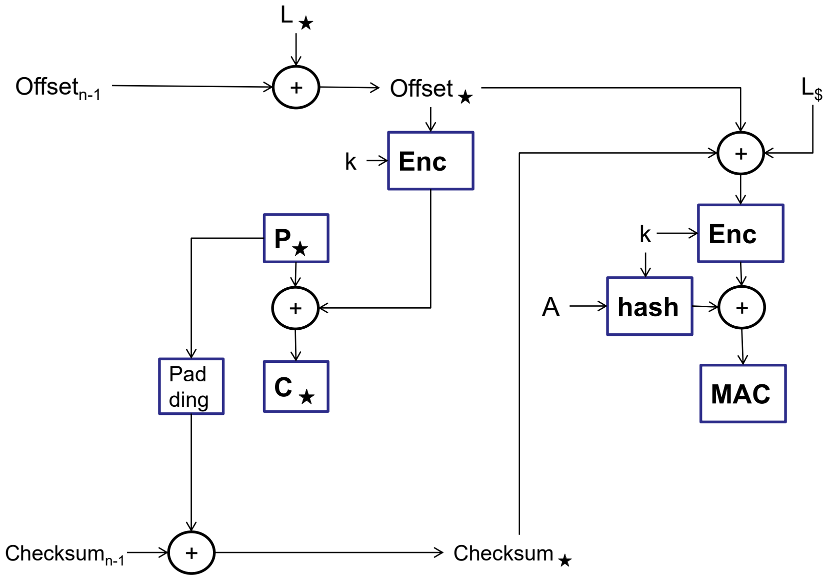
Offset Codebook Mode (OCB)



OCB Initialization

- *Offset*$_0$ depends on the key and the nonce
- "It is crucial that, as one encrypts, one does not repeat a nonce." [RFC 7253, §5.1]
- Nonce *may* not be random, e.g. a counter works fine
- A new nonce for every authenticated encryption API call is needed!
- Details about the initialization: http://www.cs.ucdavis.edu/ rogaway/ocb/ocb-faq.htm

OCB Last Block and MAC



Offset Codebook Mode (OCB)

- Question: XOR plaintext and then encrypt, that sounds like the weak MAC example from Chapter 2.2. Why is OCB more secure than the easy-to-break example?

Offset Codebook Mode (OCB)

- Question: XOR plaintext and then encrypt, that sounds like the weak MAC example from Chapter 2.2. Why is OCB more secure than the easy-to-break example?
- “OCB enjoys provable security: the mode of operation is secure assuming that the underlying blockcipher is secure. As with most modes of operation, security degrades as the number of blocks processed gets large” [RFC 7253]

Galois/Counter mode (GCM)

- Galois/Counter Mode (GCM)
  - Developed by John Viega and David A. McGrew
  - Standardized by NIST in 2007, IETF standards for cipher suites with AES-GCM for TLS (SSL) and IPSec exist.
  - Follows the Encrypt-then-MAC concept
  - Combines concept of Counter Mode for encryption with Galois Field Multiplication to compute MAC on the ciphertext
  - GF(2^{128}) based on polynomial $x^{128} + x^7 + x^2 + x + 1$

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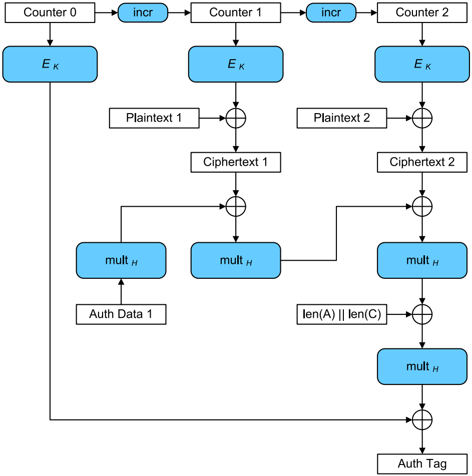
  - GF(2^{128}) based on polynomial $x^{128} + x^7 + x^2 + x + 1$
- Definitions
  - H is Enc(k,0)
  - Auth Data is data not to be encrypted. GCM generates check value by XOR and GF multiplication with H for each block.
  - For the MAC, this process continues on the ciphertext and a length field in the end.

Galois/Counter mode (GCM)



[1]

- Counter 0 = IV, Auth Tag = MAC

[1] Image Source = `https://en.wikipedia.org/wiki/Galois/Counter_Mode`

Galois Field Multiplication

- In a Galois Field we consider the bitstring to represent a polynomial.
  - E.g. $1011 = x^3 + x + 1$
- As a consequence Galois Field Multiplication is based on polynomial multiplication modulus the polynomial of the field.

Galois Field Multiplication

- In a Galois Field we consider the bitstring to represent a polynomial.
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- As a consequence Galois Field Multiplication is based on polynomial multiplication modulus the polynomial of the field.
- Example: In $GF(2^{128})$ based on polynomial $g(x) = x^{128} + x^7 + x^2 + x + 1$
  - $P(x) = x^{127} + x^7$
  - $Q(x) = x^5 + 1$
  - $P(x) \cdot Q'(x) = x^{132} + x^{127} + x^{12} + x^7$
  - To compute the modulus, we have to compute a polynomial division $P(x) * Q(x)/g(x)$.
  - We can see that $x^4 * g(x)$ removes the x^{132}, so $P(x) * Q(x) - x^4 * g(x) = x^{127} + x^{12} + x^{11} + x^7 + x^6 + x^5 + x^4$
  - Since this polynomial fits into the 128 bit, this is the remainder of the division, thus the result, in bits: 1000...011000111

Chapter 11: Secure Channel

Secure Channel

MAC-then-Enc vs. Enc-then-MAC

Secure Channel Implementation

Secure Channel (ESP) in the OpenBSD Kernel

Authenticated Encryption With Associated Data

Attacks against a Secure Channel (Stream Cipher)

Attacks against a Secure Channel (Padding oracle)

Attacks against a Secure Channel (Stream Cipher)

- Re-Use of Initialization Vector (IV):

IV, k → 1 0 1 1 0 0 0 1 0 1 0 1 1 0 0 0 1 0 1

xor

P1 = 0 0 1 0 0 0 1 0 1 0 1 1 0 1 0 1 0 1 0

C1 = 1 0 0 1 0 0 1 1 1 1 1 0 1 1 0 1 1 1 1

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xor

P1 = 0 0 1 0 0 0 1 0 1 0 1 1 0 1 0 1 0 1 0

C1 = 1 0 0 1 0 0 1 1 1 1 1 0 1 1 0 1 1 1 1

  - Then some time later the same IV is used again:

IV, k $\rightarrow \boxed{} \rightarrow$ 1 0 1 1 0 0 0 1 0 1 0 1 1 0 0 0 1 0 1

xor

P2 = 1 1 0 0 0 0 0 0 0 0 1 1 1 1 1 0 1 1

C2 = 0 1 1 1 0 0 0 1 0 1 0 0 0 1 1 1 1 1 0

Attacks against a Secure Channel (Stream Cipher)

- Re-Use of Initialization Vector (IV) continued:

$$
\begin{aligned}
C1 &= 1\ 0\ 0\ 1\ 0\ 0\ 1\ 1\ 1\ 1\ 1\ 0\ 1\ 1\ 0\ 1\ 1\ 1\ 1 \\
C2 &= 0\ 1\ 1\ 1\ 0\ 0\ 0\ 1\ 0\ 1\ 0\ 0\ 0\ 1\ 1\ 1\ 1\ 1\ 0 \\
C1 + C2 &= 1\ 1\ 1\ 0\ 0\ 0\ 1\ 0\ 1\ 0\ 1\ 0\ 1\ 0\ 1\ 0\ 0\ 0\ 1 \\
&\qquad\qquad == \qquad\qquad (\rightarrow P1{+}P2{=}C1{+}C2) \\
P1 + P2 &= 1\ 1\ 1\ 0\ 0\ 0\ 1\ 0\ 1\ 0\ 1\ 0\ 1\ 0\ 1\ 0\ 0\ 0\ 1 \\
P1 &= 0\ 0\ 1\ 0\ 0\ 0\ 1\ 0\ 1\ 0\ 1\ 1\ 0\ 1\ 0\ 1\ 0\ 1\ 0 \\
P2 &= 1\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 1\ 1\ 1\ 1\ 1\ 0\ 1\ 1
\end{aligned}
$$

- As we see from the example, the attacker can computer C1+C2 because he observes C1 and C2, but that means he knows also P1+P2.
- Known Plaintext (e.g. P1) $\rightarrow$ attacker can compute other plaintext
- Statistical properties of plaintext can be used if plaintext is not random-looking. That means if entropy of P1+P2 is low.

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Attacks against a Secure Channel (Padding oracle)

Guessing a secret (revisited)

- Passwords
  - N: size of alphabet (number of different characters)
  - L: length of password in characters
- Complexity of guessing a randomly-generated password / secret
  - The assumption is, we generate a password and then we test it.
    $\rightarrow \mathcal{O}(N^L)$
- Complexity of guessing a randomly-generated password character by character
  - The assumption is that we can check each character individually for correctness.
  - For each character it is $N/2$ (avg) and N (worst case)
  - So, overall $L * N/2$ (avg)
- In the subsequent slides we will show an attack that reduces the decryption of a blockcipher in CBC mode to byte-wise decryption (under special assumptions).

MAC-then-Encrypt-Issues

P	MAC
Ciphertext	

- Operation
  - P and MAC are encrypted and hidden in the ciphertext.
  - Receiver
    - Decrypts P
    - Decrypts MAC
    - Computes and checks MAC $\rightarrow$ MAC error or success

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- Operation
  - P and MAC are encrypted and hidden in the ciphertext.
  - Receiver
    - Decrypts P
    - Decrypts MAC
    - Computes and checks MAC $\rightarrow$ MAC error or success
- Consequence
  - MAC does not protect the ciphertext.
  - Integrity check can only be done once everything is decrypted.
  - As a consequence, receiver will detect malicious messages at the end of the secure channel processing and not earlier.
  - But is that more than a performance issue? Well, yes.

MAC-then-Encode-then-Encrypt

- If we use a block cipher, we have to ensure that the message encoding fits to the blocksize of the cipher.
- Encode-then-MAC-then-Encrypt:

P	Pad	MAC
Ciphertext		

  - Format P so that with the MAC added the encryption sees the right size.
  - Needs that we know the size of the MAC and blocksize of cipher when generating P | Padding.

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- MAC-then-Encode-then-Encrypt:

P	MAC	Pad
Ciphertext		

  - Used in TLS/SSL
  - Here, we add the MAC first and then üad the P | MAC to the correct size.
  - How do we know what is padding and what not? Padding in TLS/SSL:
    - If size of padding is 1 byte, the padding is 1.
    - If size of padding is 2 bytes, the padding is 2 2.
    - If size of padding is 3 bytes, the padding is 3 3 3.
    - . . .

Oracles and Side Channels

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Oracles and Side Channels

- In ancient times, people asked oracles for guidance.
- In computer science, oracles are functions that give as cheaply access to information that would otherwise be hard to compute.
  - E.g. $\mathcal{O}(1)$ cost to ask specific NP-complete question $\rightarrow$ polynomial hierarchy
- In cryptography, an attacker can trigger some participant O in a protocol or communication to leak information that might or might not be useful.
  - Participant O may re-encrypt some message fragment
  - Participant O responds with an error message explaining what went wrong
  - Response time of participant O may indicate where error happened
  - Response time may leak information about key if processing time depends (enough) on which bits are set to 1.
    - More obvious for the computationally expensive public key algorithms, but implementations of symmetric ciphers have also been attacked.

Side Channels and padding Oracles

- Side Channel Attacks
  - A general class of attacks where the attacker gains information from aspects of the physical implementation of a cryptosystem.
  - Can be based on: Timing, Power Consumption, Radiation,...

P	Pad
Ciphertext	

ok

Side Channels and padding Oracles

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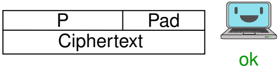


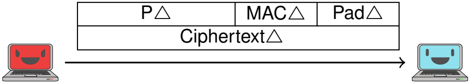
- Padding Oracle
  - The oracle tells the attacker if the padding in the message was correct.
  - This may be due to a message with the information.
  - It can also be due to side channel like the response time.

Concept of Padding Oracle Attack (against CBC)

- Attacker sees unknown ciphertext C =

P	MAC	Pad
Ciphertext		

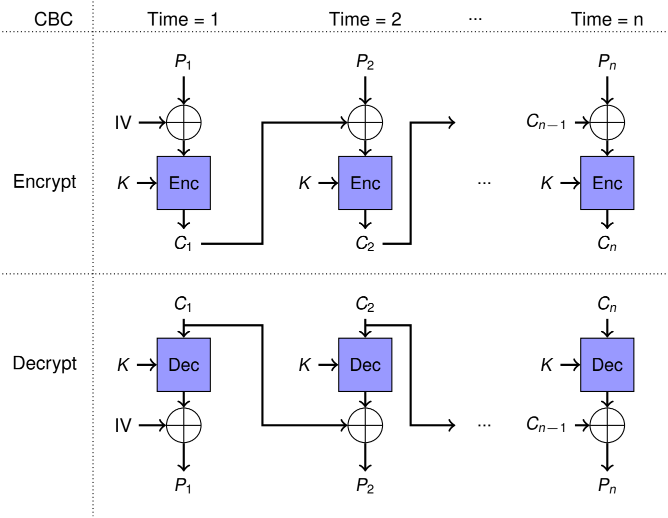
  that was sent from Alice to Bob
- To decrypt the ciphertext, the attacker modifies C and sends it to Bob.



- It is unlikely that the MAC and padding are correct. So, Bob will send an error back to Alice (and the attacker).
- In earlier versions of TLS, Bob sent back different error messages for padding errors and for MAC errors.

Padding Oracle Attack - CBC mode decryption (revisited)

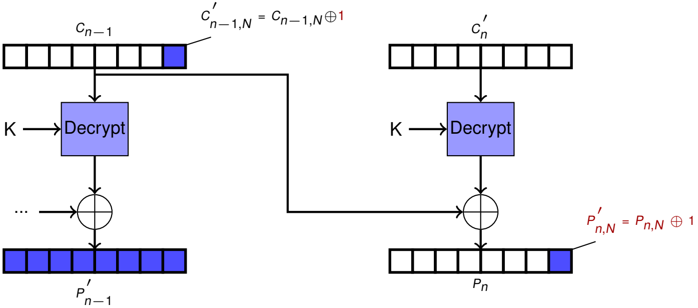
- Encryption and Decryption in CBC mode



Padding Oracle Attack against CBC

- Assumptions:
  - Attacker got hold of a ciphertext C (n blocks, N bytes per block)
    - C was protected with Encryption in CBC mode used in MAC-then-Encode-then-Encrypt mode.
    - For padding PKCS7 was used (padding of 1 byte: pad = 1, padding 2 bytes: pad = 2 2, ...)
  - An oracle replies to sent ciphertexts with error messages:
    - Padding error if padding doesn't match (checked before MAC).
    - MAC error if padding fits but MAC is wrong.
- Goal: Decrypt the complete ciphertext using the oracle.
- Approach:
  - Start decrypting the last byte of the last block $P_{n,N}$ by altering $C_{n-1,N}$ and sending the resulting ciphertext C' to the oracle.
  - When the oracle replies with a MAC error $P_{n,N}$ can be calculated (see following slides).

- Change the last byte of the original ciphertext block C_{n-1} by XORing it with a chosen $\triangle$: $C'_{n-1,N} = C_{n-1,N} \oplus \triangle$. Then send C' to the oracle.
- Padding error returned:
  - Try again using a new $\triangle$ (max of 256 tries needed).



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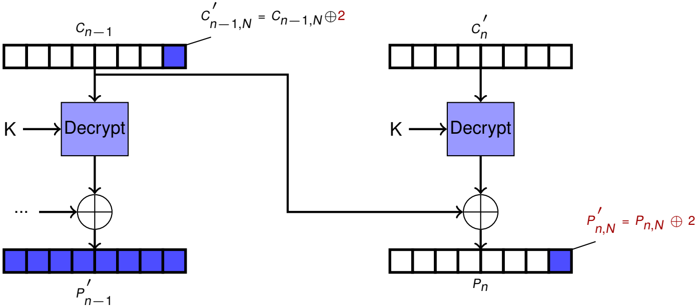

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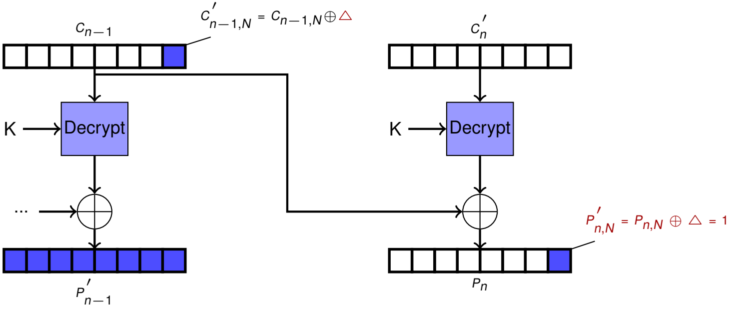
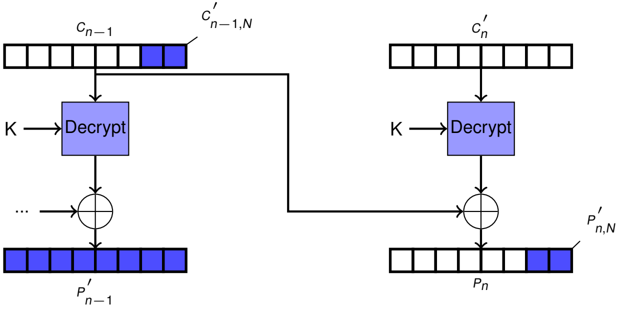
- Padding error returned:
  - Try again using a new $\triangle$ (max of 256 tries needed).
- MAC error:
  - padding was fine $\rightarrow P'_{n,N} = 1$ (since a padding size of 1 byte means padding=$P'_{n,N} = 1$)
  - correct padding means the last byte was 1 $\rightarrow P'_{n,N} = P_{n,N} \oplus \triangle = 1 \rightarrow P_{n,N} = 1 \oplus \triangle$



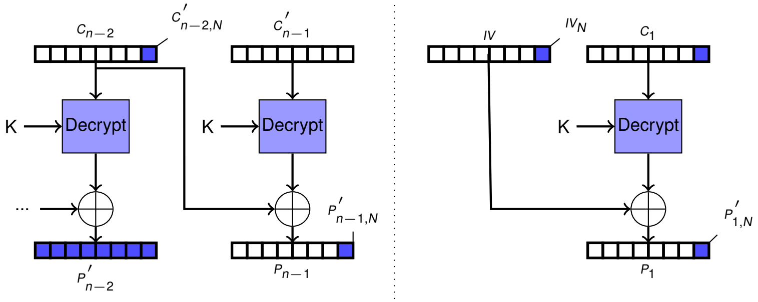
Padding Oracle Attack against CBC

- Now we want to decrypt $P_{n,N-1}$. For that a padding of length 2 is needed.
- Since $P_{n,N}$ is known, we can calculate $C'_{n-1,N}$ so that $P'_{n,N} = 2$
  - $P_{n,N} \oplus C'_{n-1,N} = 2 \rightarrow C'_{n-1,N} = P_{n,N} \oplus 2$
- Now find $C'_{n-1,N-1}$ that satisfies $C'_{n-1,N} \oplus P_{n,N-1} = 2$



- As before, we need to try up to 256 values, all values except for the correct one generate a padding error. The correct one produces a MAC error. $\rightarrow$ We know $P_{n,N-1}$

- To completely decrypt C_n we have to repeat the procedure until all bytes of the block are decrypted. In the figure with 8 bytes per block, the last padding we generate is 8 8 8 8 8 8 8 8.
- To decrypt C_{n-1} we can cut off C_n and repeat the same procedure with C_{n-1} as last block. For decrypting C_1 we can use the IV as ciphertext for the attack modifications.



Final remarks

- The attack was against CBC mode used in MAC-then-Encode-then-Encrypt mode.
  - Padding Oracle attack known long in cryptography.
  - Mode still used in SSL / TLS. Hacks have utilized that. However, defenses have been added.
- CBC with Encode-then-Encrypt-then-MAC does not have this vulnerability.
  - Because MAC check would fail first, process would be aborted, and padding problems would then not be leaked.

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