Constant-time programing in FaCT

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Gary Soeller, Deian Stefan, Riad Wahby, Conrad Watt

Timing side channels

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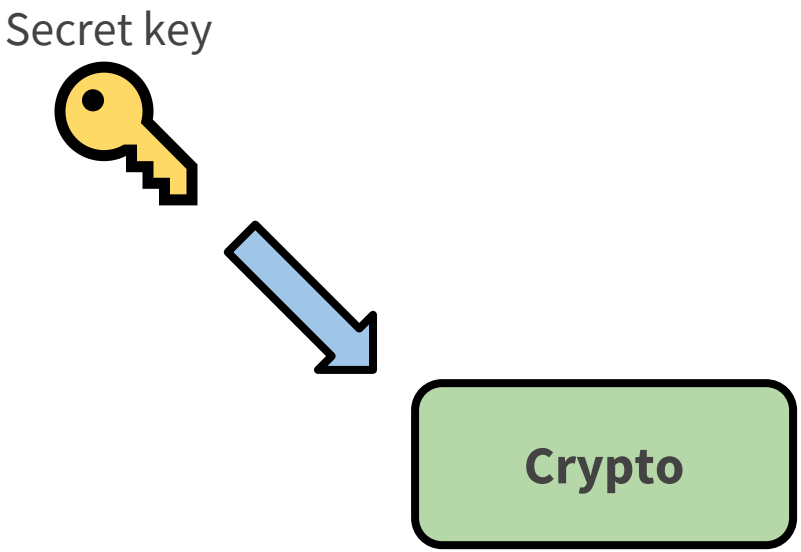
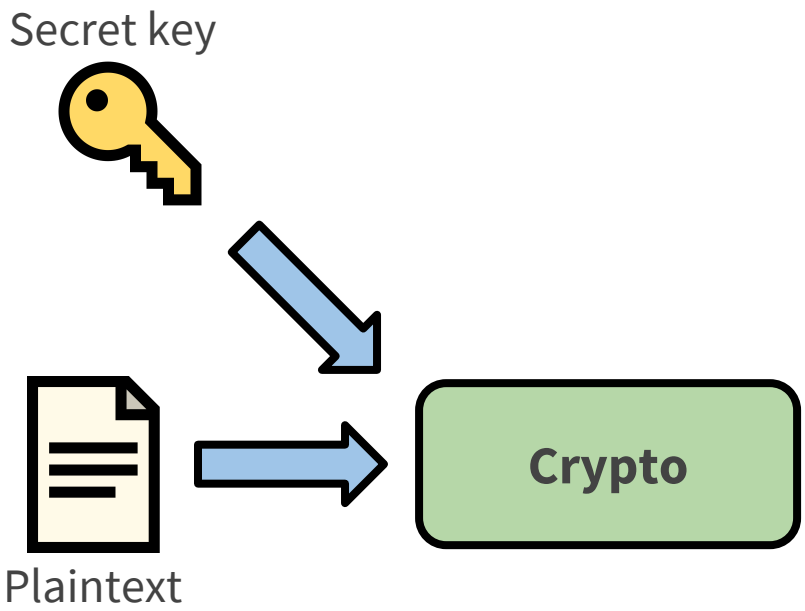


Timing side channels



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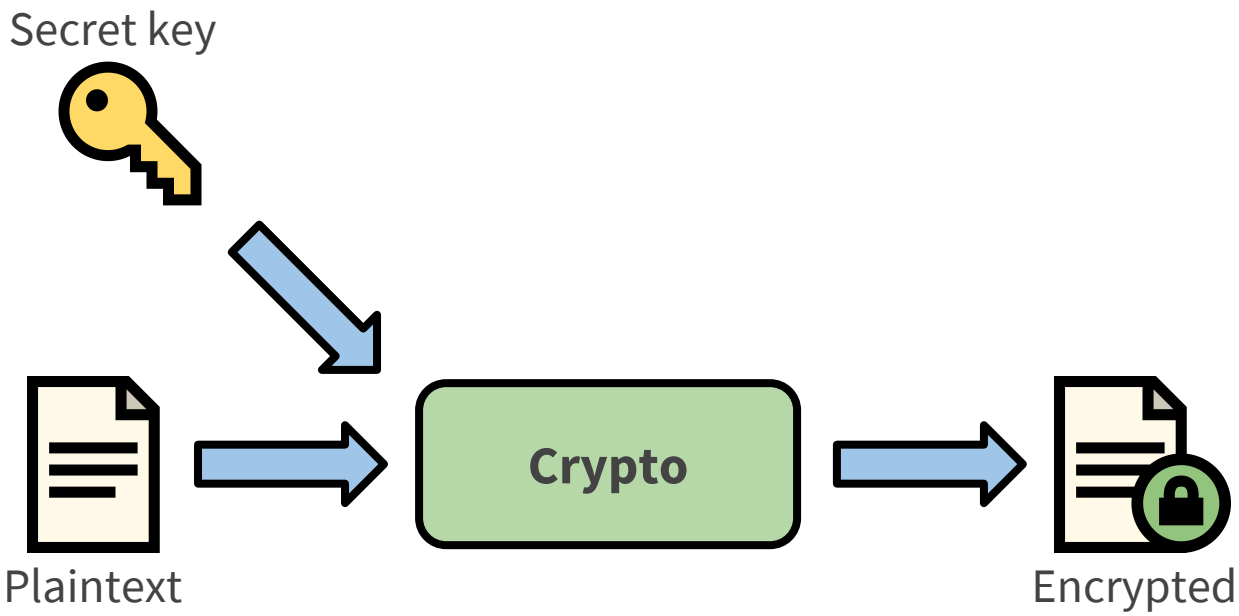
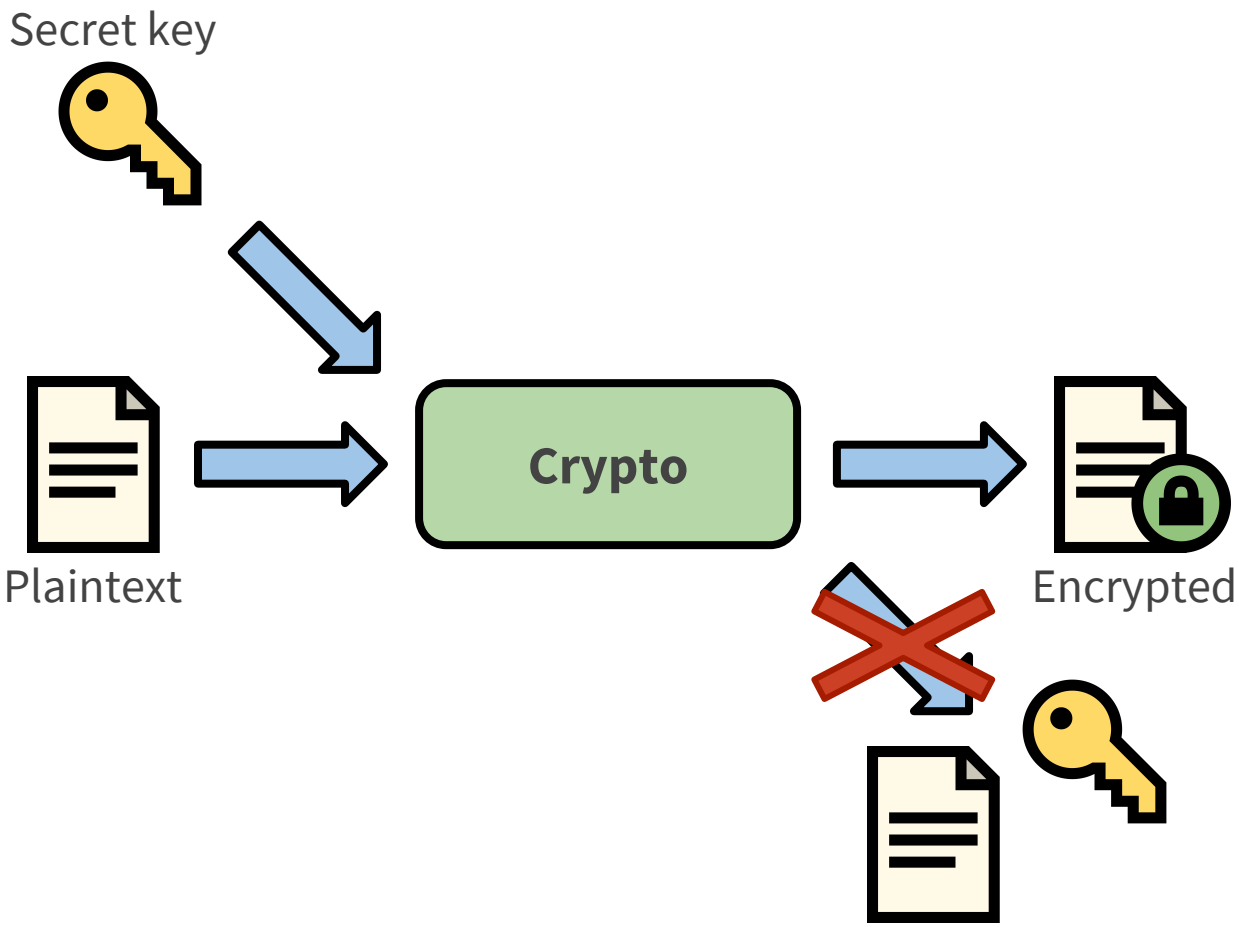
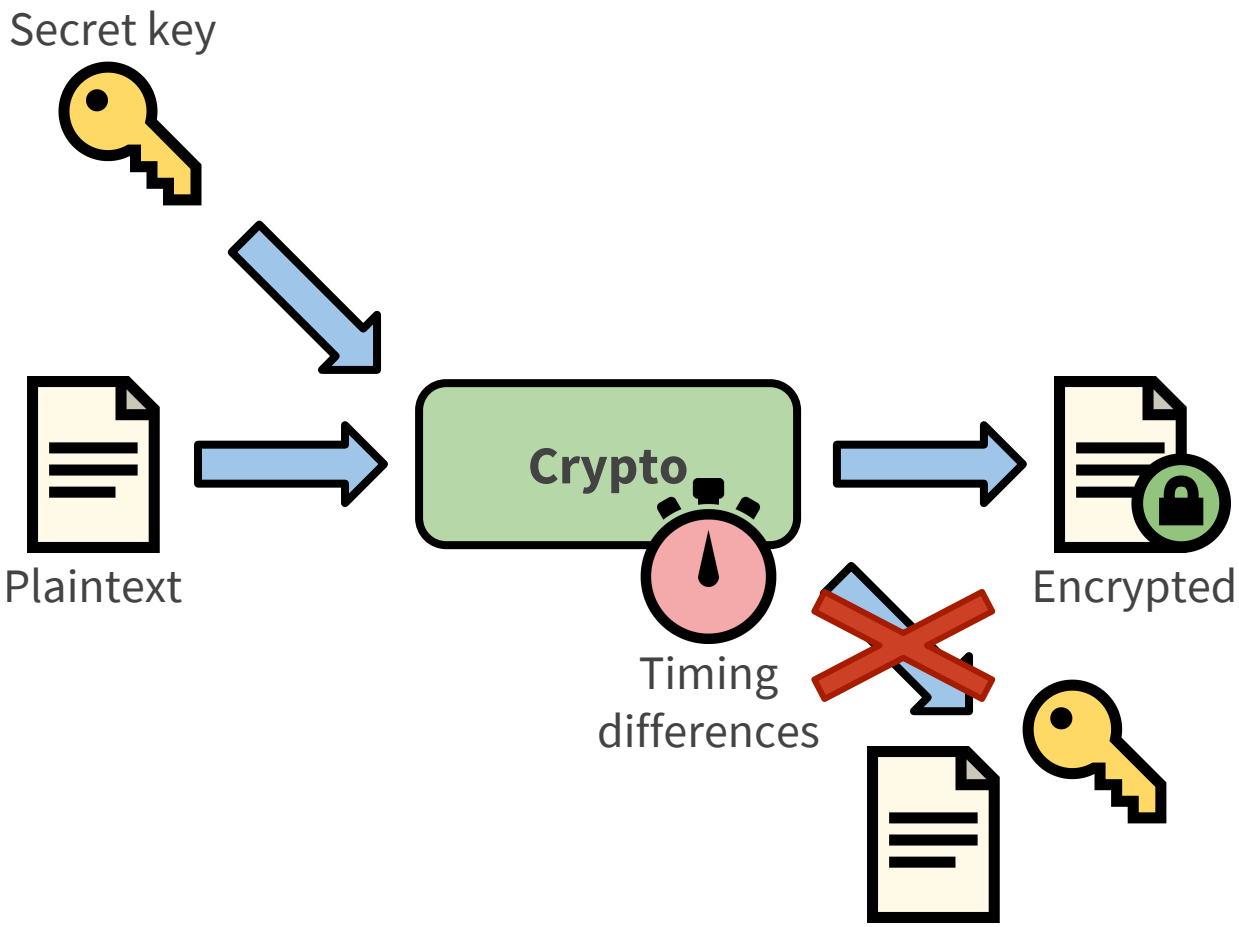


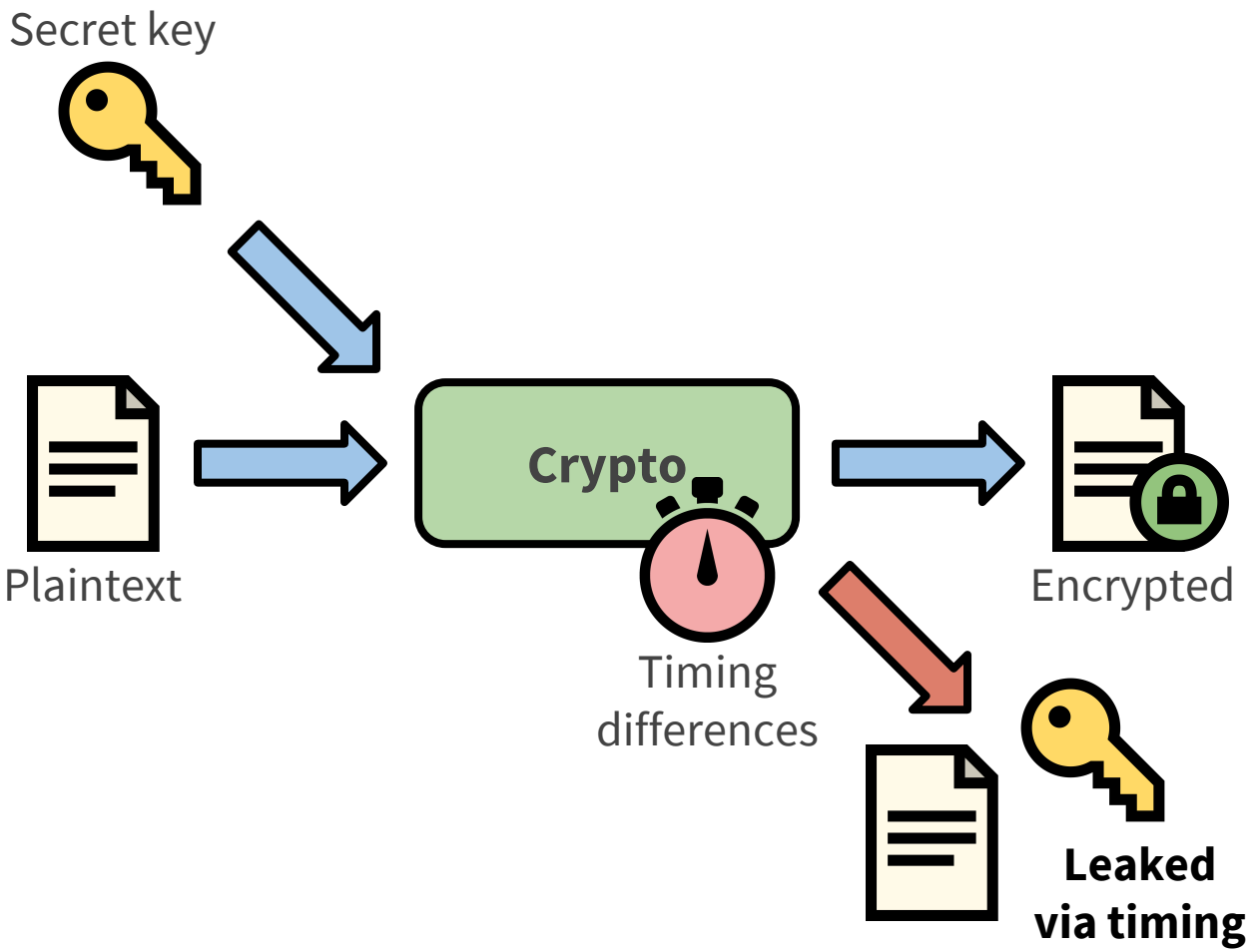
Timing side channels



Timing side channels



Timing side channels



Constant-time coding example

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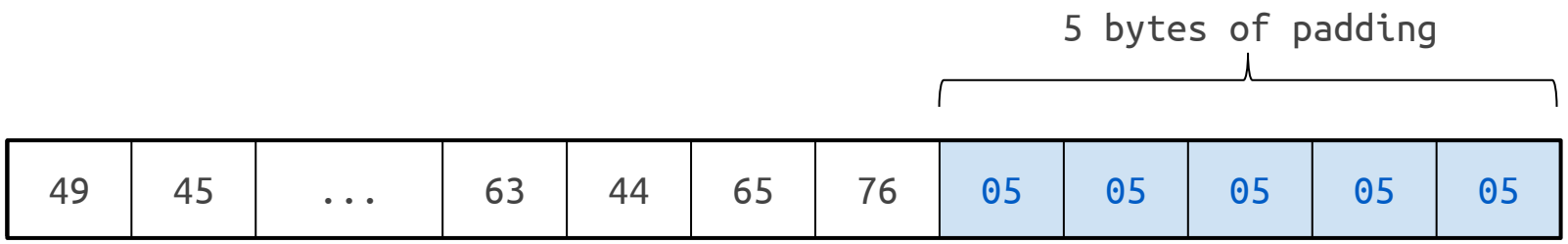

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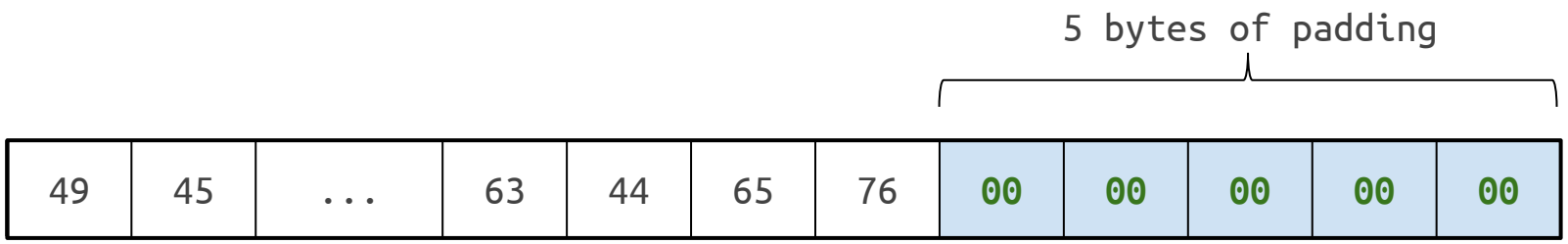
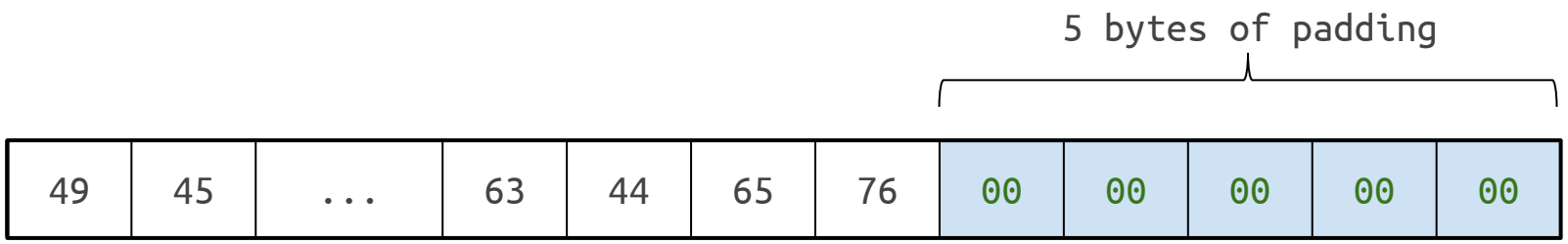
- Replace padding with null bytes
- Return padding length, or error



Constant-time coding example

- Check for valid padding
  - PKCS #7 padding
  - Each padding byte holds length of padding
- Replace padding with null bytes
- Return padding length, or error

- Must be careful: buffer contents are secret
  - That includes padding!



```
int32_t remove_padding(
    uint8_t* buf,
    uint32_t buflen) {

  uint8_t padlen = buf[buflen-1];
  uint32_t i;
  for (i = 0; i < padlen; i++) {
    if (buf[buflen-i-1] != padlen)
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  }
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```

49	45	...	63	44	65	76	05	05	05	05	05

```c
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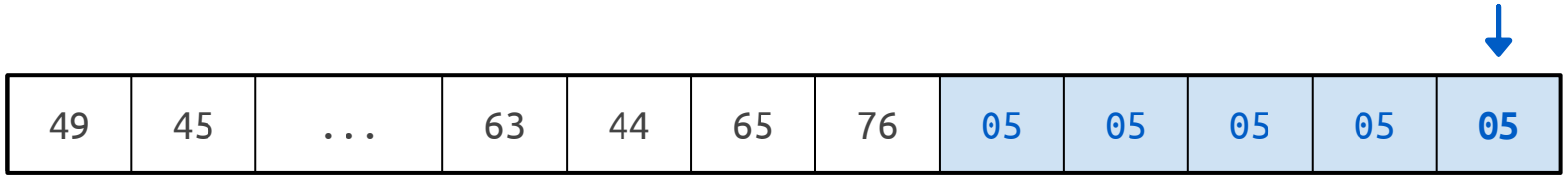

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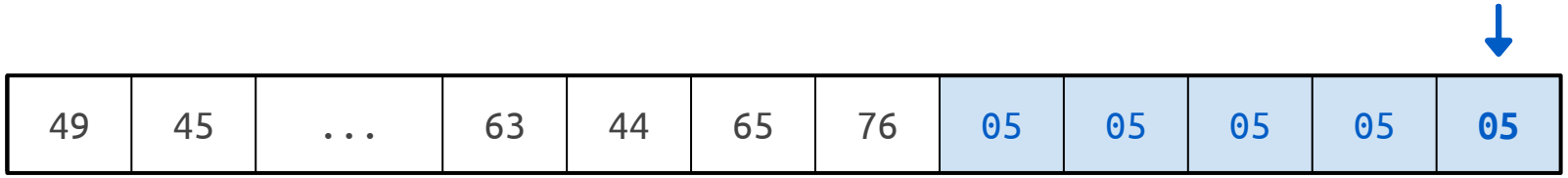

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49	45	...	63	44	65	76	05	05	05	05	**05**

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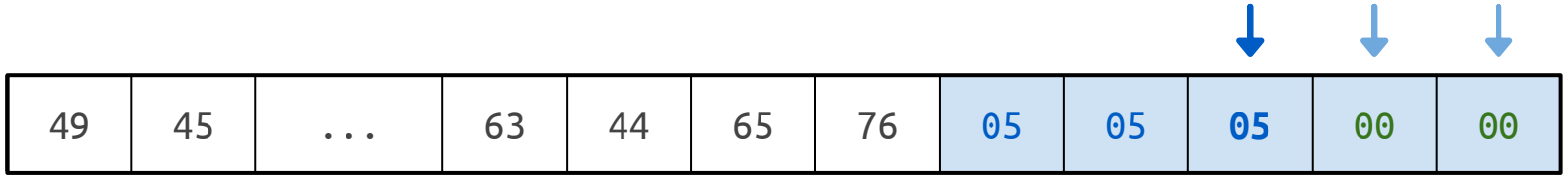

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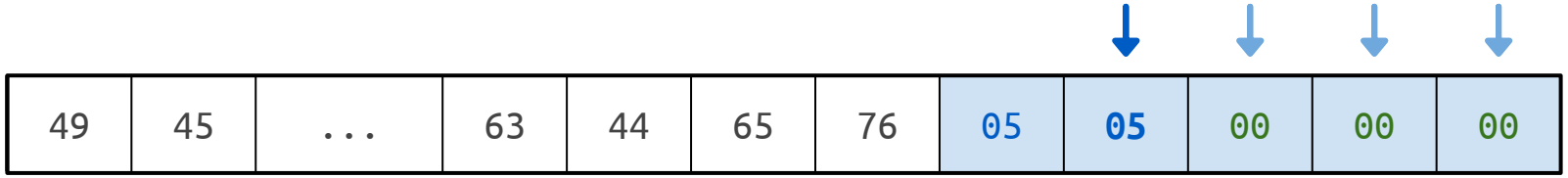

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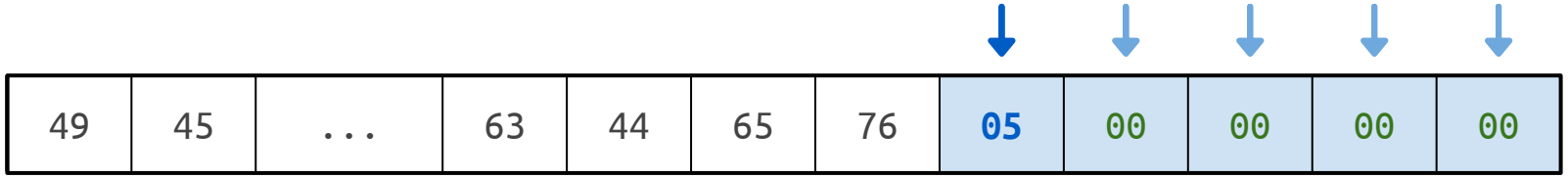

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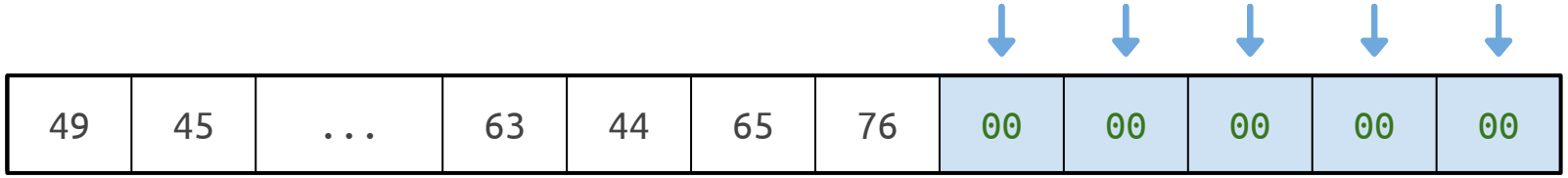

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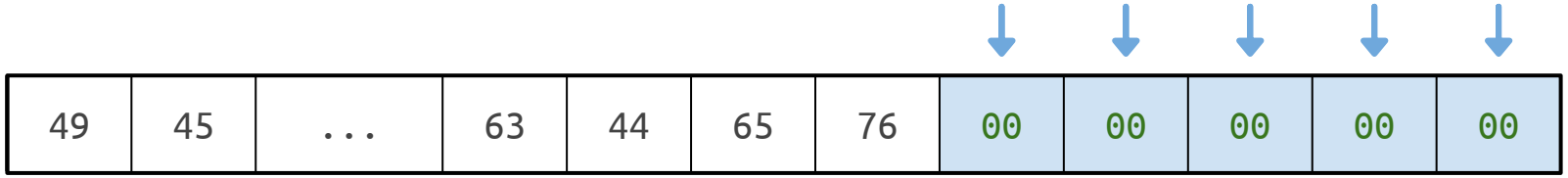

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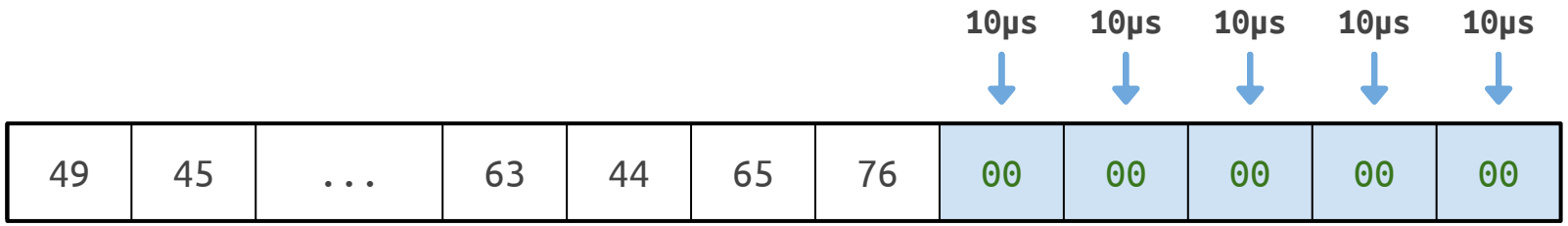

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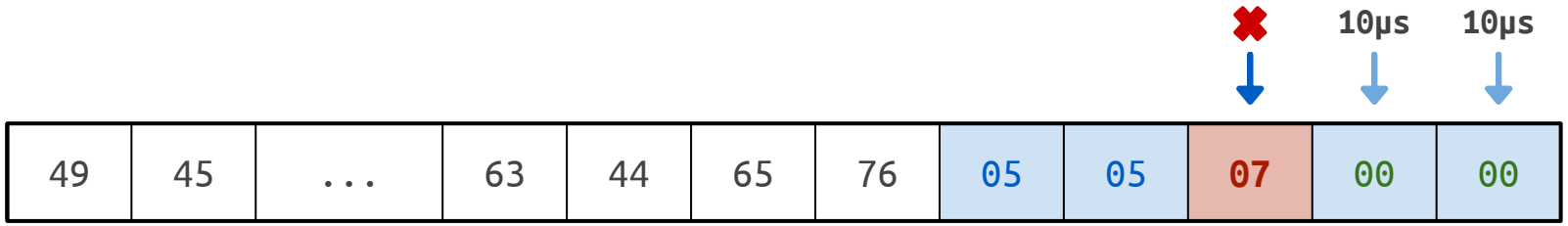

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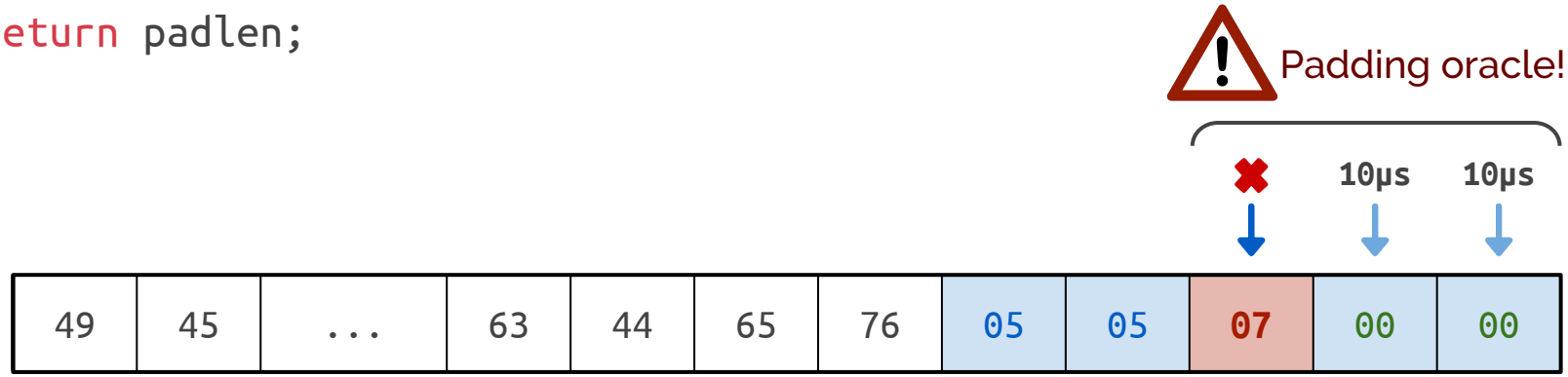

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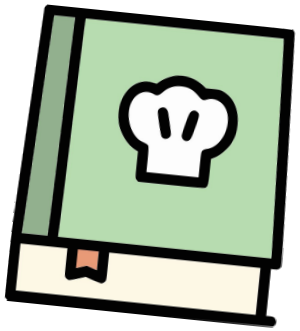
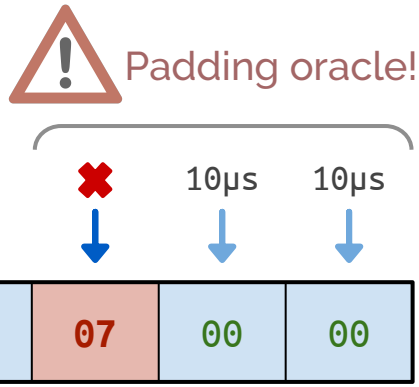
```

It's dangerous to return early!



Use this instead.



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int32_t remove_padding2(
    uint8_t* buf,
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  uint8_t ok = 1;
  uint8_t padlen = buf[buflen-1];
  uint32_t i;
  for (i = 0; i < padlen; i++) {
    if (buf[buflen-i-1] != padlen)
      ok = 0;
    buf[buflen-i-1] = 0;
  }
  return ok ? padlen : -1;
}
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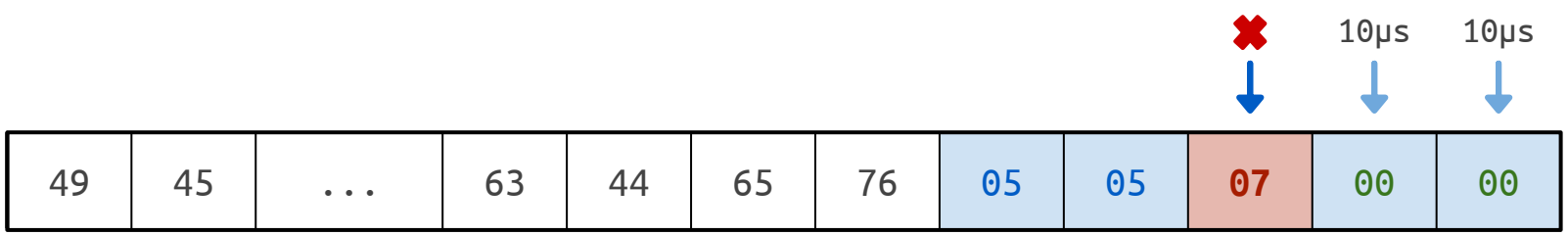

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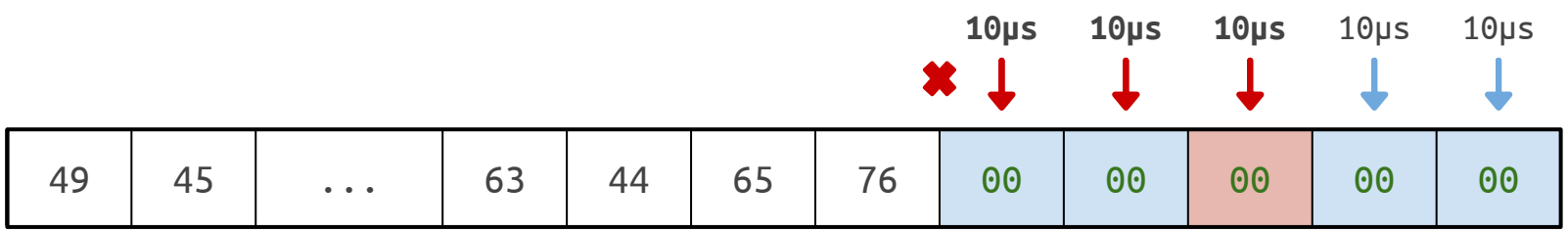

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49	45	...	63	44	65	76	31	37	**03**	**03**	**03**

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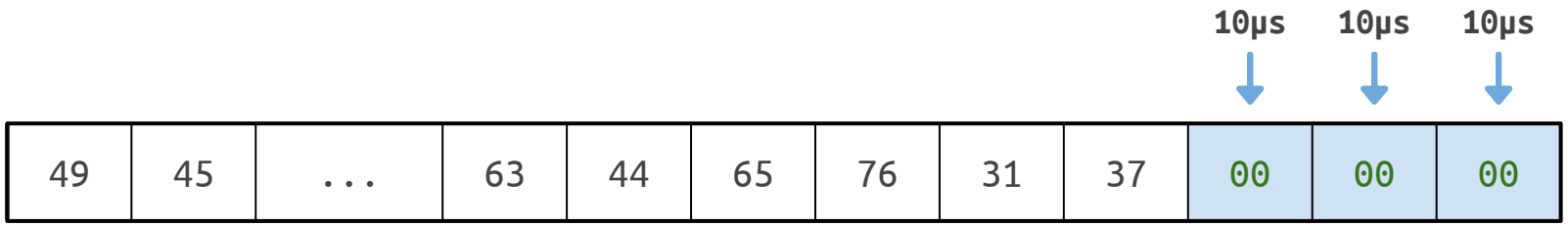

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    buf[buflen-i-1] = 0;
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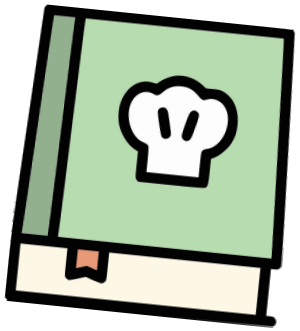
}
```

It's dangerous to bound loops with secrets!



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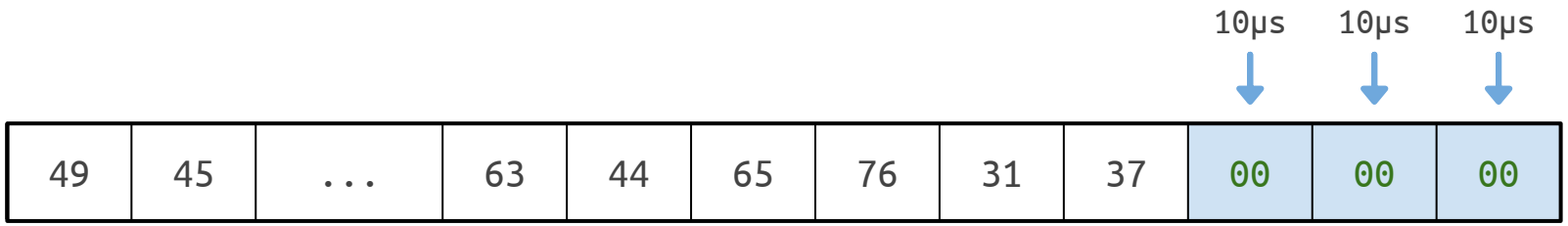

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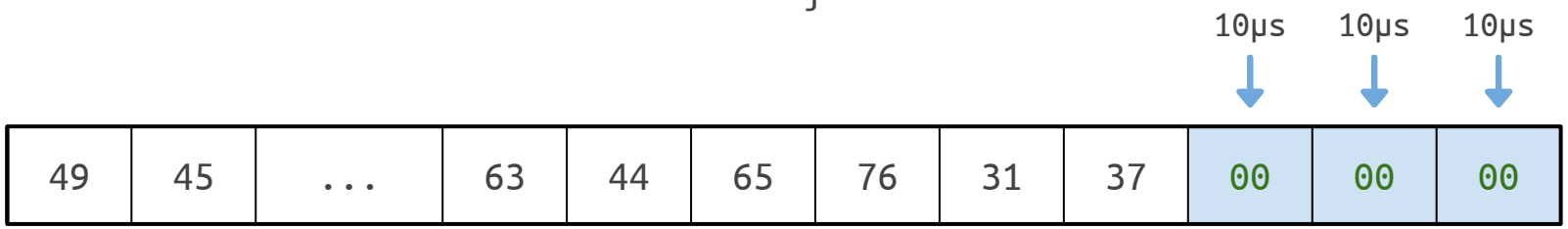
    buf[buflen-i-1] = 0;
  }
  return ok ? padlen : -1;
}
```

```
int32_t remove_padding3(
    uint8_t* buf,
    uint32_t buflen) {
  uint8_t ok = 1;
  uint8_t padlen = buf[buflen-1];
  uint32_t i;
  for (i = buflen-255; i < buflen; i++) {
    uint8_t b = buf[i];
    if (i >= buflen - padlen) {
      if (b != padlen)
        ok = 0;
      b = 0;
    }
    buf[i] = b;
  }
  return ok ? padlen : -1;
}
```



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  uint8_t ok = 1;
  uint8_t padlen = buf[buflen-1];
  uint32_t i;
  for (i = 0; i < padlen; i++) {
    if (buf[buflen-i-1] != padlen)
      ok = 0;
    buf[buflen-i-1] = 0;
  }
  return ok ? padlen : -1;
}
```

```c
int32_t remove_padding3(
    uint8_t* buf,
    uint32_t buflen) {
  uint8_t ok = 1;
  uint8_t padlen = buf[buflen-1];
  uint32_t i;
  for (i = buflen-255; i < buflen; i++) {
    uint8_t b = buf[i];
    if (i >= buflen - padlen) {
      if (b != padlen)
        ok = 0;
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    }
    buf[i] = b;
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}
```
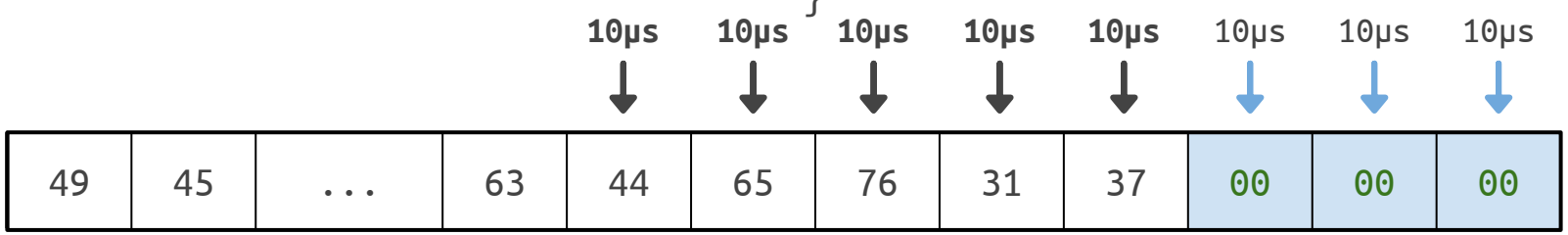
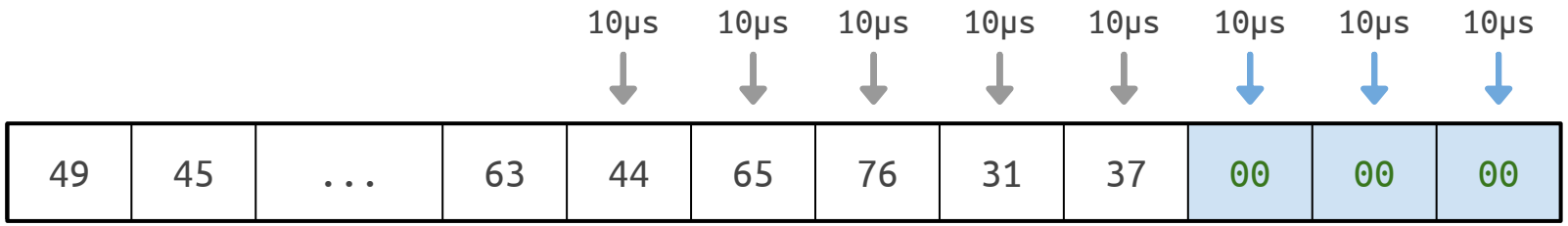
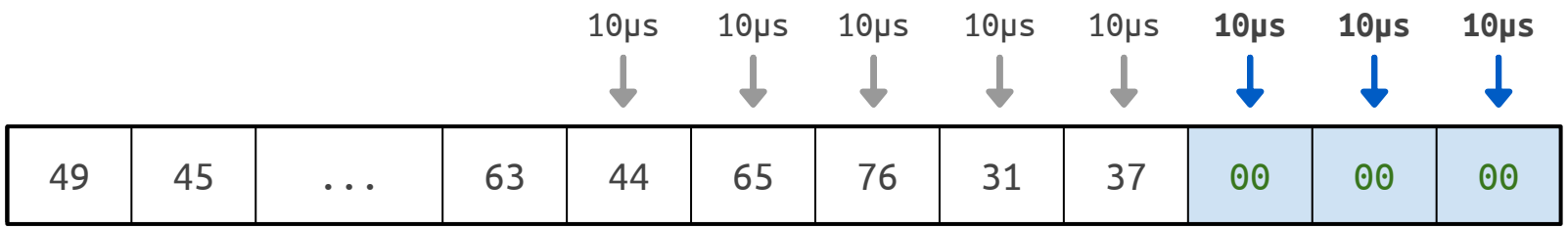



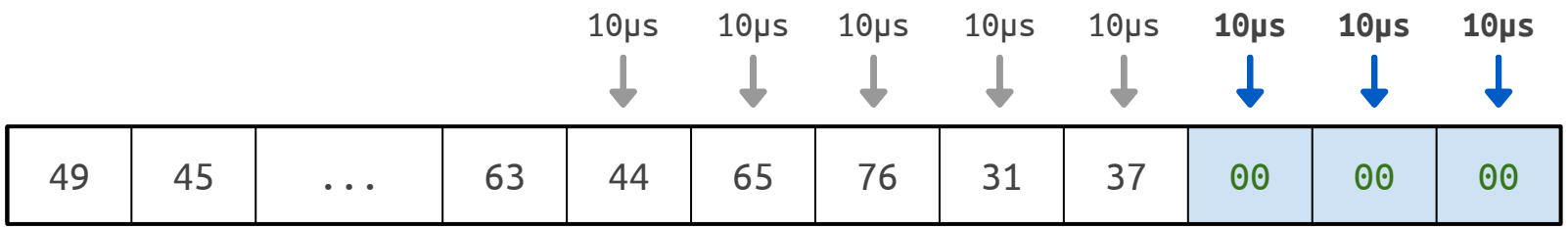
```
int32_t remove_padding3(
    uint8_t* buf,
    uint32_t buflen) {
  uint8_t ok = 1;
  uint8_t padlen = buf[buflen-1];
  uint32_t i;
  for (i = buflen-255; i < buflen; i++) {
    uint8_t b = buf[i];
    if (i >= buflen - padlen) {
      if (b != padlen)
        ok = 0;
      b = 0;
    }
    buf[i] = b;
  }
  return ok ? padlen : -1;
}
```



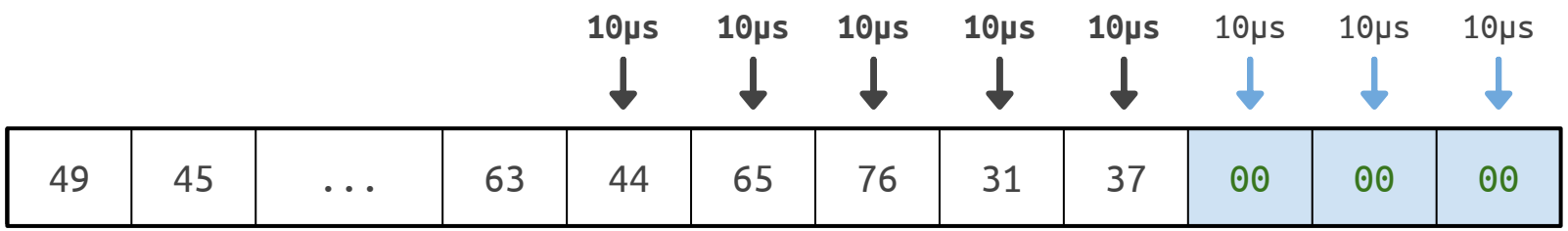
```c
int32_t remove_padding3(
    uint8_t* buf,
    uint32_t buflen) {
  uint8_t ok = 1;
  uint8_t padlen = buf[buflen-1];
  uint32_t i;
  for (i = buflen-255; i < buflen; i++) {
    uint8_t b = buf[i];
    if (i >= buflen - padlen) {
      if (b != padlen)
        ok = 0;
      b = 0;
    }
    buf[i] = b;
  }
  return ok ? padlen : -1;
}
```



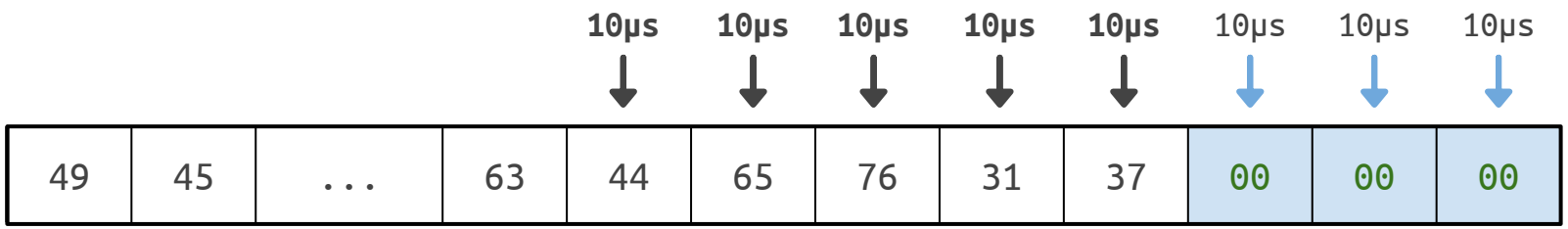
```
int32_t remove_padding3(
    uint8_t* buf,
    uint32_t buflen) {
  uint8_t ok = 1;
  uint8_t padlen = buf[buflen-1];
  uint32_t i;
  for (i = buflen-255; i < buflen; i++) {
    uint8_t b = buf[i];
    if (i >= buflen - padlen) {
      if (b != padlen)
        ok = 0;
      b = 0;
    }
    buf[i] = b;
  }
  return ok ? padlen : -1;
}
```



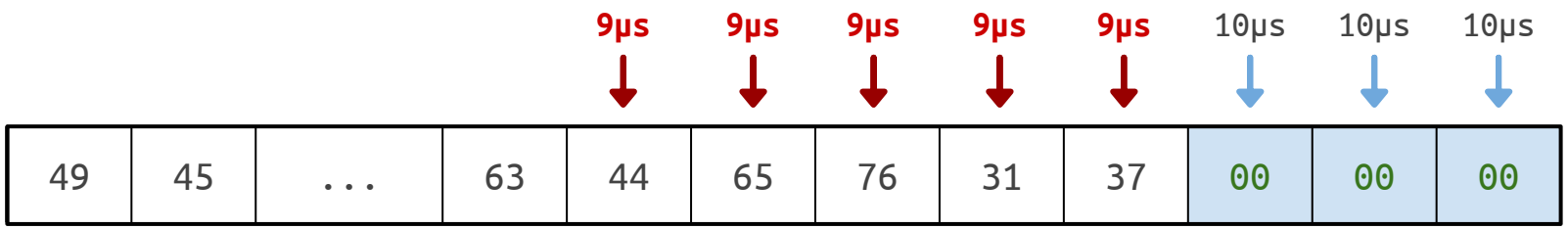
```c
int32_t remove_padding3(
    uint8_t* buf,
    uint32_t buflen) {
  uint8_t ok = 1;
  uint8_t padlen = buf[buflen-1];
  uint32_t i;
  for (i = buflen-255; i < buflen; i++) {
    uint8_t b = buf[i];
    if (i >= buflen - padlen) {
      if (b != padlen)
        ok = 0;
      b = 0;
    }
    buf[i] = b;
  }
  return ok ? padlen : -1;
}
```



```
int32_t remove_padding3(
    uint8_t* buf,
    uint32_t buflen) {
  uint8_t ok = 1;
  uint8_t padlen = buf[buflen-1];
  uint32_t i;
  for (i = buflen-255; i < buflen; i++) {
    uint8_t b = buf[i];
    if (i >= buflen - padlen) {
      if (b != padlen)
        ok = 0;
      b = 0;
    }
    buf[i] = b;
  }
  return ok ? padlen : -1;
}
```

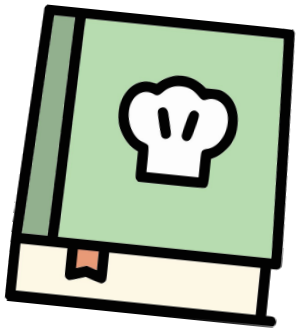


```
int32_t remove_padding3(
    uint8_t* buf,
    uint32_t buflen) {
  uint8_t ok = 1;
  uint8_t padlen = buf[buflen-1];
  uint32_t i;
  for (i = buflen-255; i < buflen; i++) {
    uint8_t b = buf[i];
    if (i >= buflen - padlen) {
      if (b != padlen)
        ok = 0;
      b = 0;
    }
    buf[i] = b;
  }
  return ok ? padlen : -1;
}
```

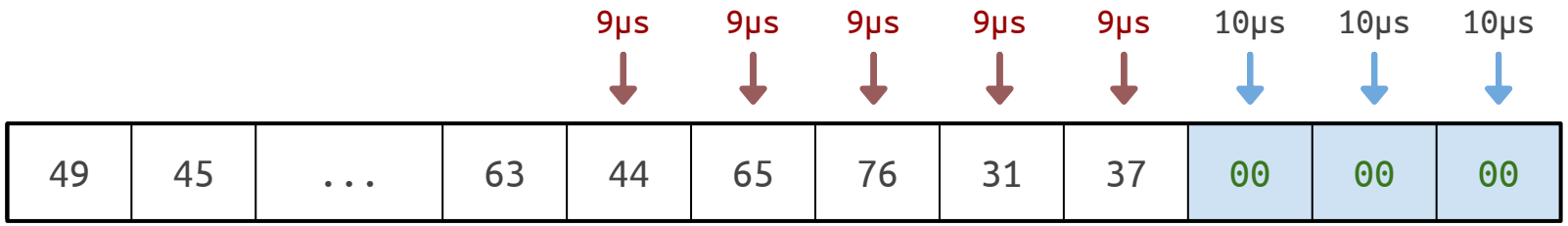


```c
int32_t remove_padding3(
    uint8_t* buf,
    uint32_t buflen) {
  uint8_t ok = 1;
  uint8_t padlen = buf[buflen-1];
  uint32_t i;
  for (i = buflen-255; i < buflen; i++) {
    uint8_t b = buf[i];
    if (i >= buflen - padlen) {
      if (b != padlen)
        ok = 0;
      b = 0;
    }
    buf[i] = b;
  }
  return ok ? padlen : -1;
}
```

It's dangerous to have branching code!



Use this instead.



```c
int32_t remove_padding3(
    uint8_t* buf,
    uint32_t buflen) {
  uint8_t ok = 1;
  uint8_t padlen = buf[buflen-1];
  uint32_t i;
  for (i = buflen-255; i < buflen; i++) {
    uint8_t b = buf[i];
    if (i >= buflen - padlen) {
      if (b != padlen)
        ok = 0;
      b = 0;
    }
    buf[i] = b;
  }
  return ok ? padlen : -1;
}
```

Ugly! Do not read!

```c
int32_t remove_padding4(
    uint8_t* buf,
    uint32_t buflen) {
  uint32_t ok = -1;
  uint8_t padlen = buf[buflen-1];
  uint32_t i;
  for (i = buflen-255; i < buflen; i++) {
    uint8_t b = buf[i];
    uint32_t proper_index =
      ct_ge_u32(i, buflen - padlen);
    uint32_t matches_pad =
      ct_eq_u8(b, padlen);
    ok &= matches_pad & proper_index;
    b = ~proper_index & b;
    buf[i] = b;
  }
  return (ok & padlen) | ~ok;
}
```

9µs	9µs	9µs	9µs	9µs	10µs	10µs	10µs
44	65	76	31	37	00	00	00

49	45	...	63

```c
int32_t remove_padding3(
    uint8_t* buf,
    uint32_t buflen) {
  uint8_t ok = 1;
  uint8_t padlen = buf[buflen-1];
  uint32_t i;
  for (i = buflen-255; i < buflen; i++) {
    uint8_t b = buf[i];
    if (i >= buflen - padlen) {
      if (b != padlen)
        ok = 0;
      b = 0;
    }
    buf[i] = b;
  }
  return ok ? padlen : -1;
}
```

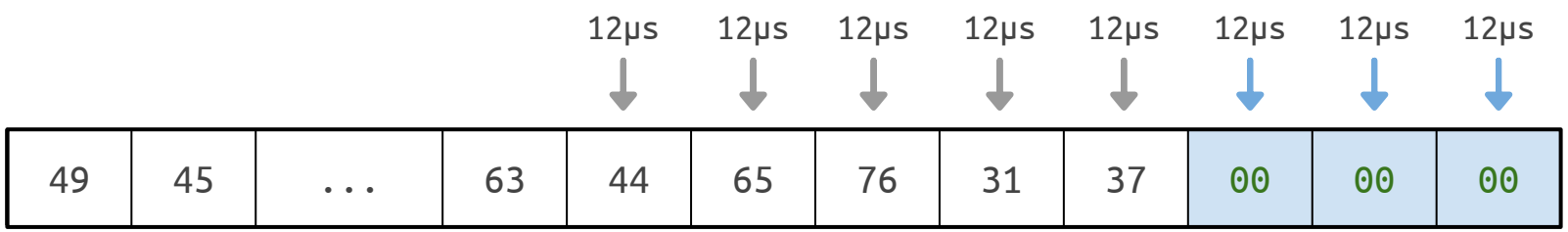
Ugly! Do not read!

```c
int32_t remove_padding4(
    uint8_t* buf,
    uint32_t buflen) {
  uint32_t ok = -1;
  uint8_t padlen = buf[buflen-1];
  uint32_t i;
  for (i = buflen-255; i < buflen; i++) {
    uint8_t b = buf[i];
    uint32_t proper_index =
      ct_ge_u32(i, buflen - padlen);
    uint32_t matches_pad =
      ct_eq_u8(b, padlen);
    ok &= matches_pad & proper_index;
    b = ~proper_index & b;
    buf[i] = b;
  }
  return (ok & padlen) | ~ok;
}
```

12µs	12µs	12µs	12µs	12µs	12µs	12µs	12µs
49	45	...	63	44	65	76	31	37	00	00	00

```
int32_t remove_padding4(
    uint8_t* buf,
    uint32_t buflen) {
  uint32_t ok = -1;
  uint8_t padlen = buf[buflen-1];
  uint32_t i;
  for (i = buflen-255; i < buflen; i++) {
    uint8_t b = buf[i];
    uint32_t proper_index = ct_ge_u32(i, buflen - padlen);
    uint32_t matches_pad = ct_eq_u8(b, padlen);
    ok &= matches_pad & proper_index;
    b = ~proper_index & b;
    buf[i] = b;
  }
  return (ok & padlen) | ~ok;
}
```

Ugly! Do not read!



Error-prone in practice

```diff
@@ -383,13 +383,10 @@ dtls1_process_record(SSL *s)
 383  383        SSL3_RECORD *rr;
 384  384        unsigned int mac_size;
 385  385        unsigned char md[EVP_MAX_MD_SIZE];
      386 +      int decryption_failed_or_bad_record_mac = 0;
 386  387
 387  388
 388  389        rr= &(s->s3->rrec);
@@ -417,13 +418,10 @@ dtls1_process_record(SSL *s)
 417  418        enc_err = s->method->ssl3_enc->enc(s,0);
 418  419        if (enc_err <= 0)
 419  420                {
 420     -              /* decryption failed, silently discard message */
 421     -              if (enc_err < 0)
 422     -                      {
 423     -                      rr->length = 0;
 424     -                      s->packet_length = 0;
 425     -                      }
 426     -              goto err;
      421 +              /* To minimize information leaked via timing, we will always
      422 +               * perform all computations before discarding the message.
      423 +               */
      424 +              decryption_failed_or_bad_record_mac = 1;
 427  425                }
 428  426
 429  427 #ifdef TLS_DEBUG
@@ -453,7 +451,7 @@ printf("\n");
 453  451                        SSLerr(SSL_F_DTLS1_PROCESS_RECORD,SSL_R_PRE_MAC_LENGTH_TOO_LONG);
 454  452                        goto f_err;
 455  453 #else
 456     -                      goto err;
      454 +                      decryption_failed_or_bad_record_mac = 1;
 457  455 #endif
 458  456                        }
 459  457                /* check the MAC for rr->input (it's in mac_size bytes at the tail) */
@@ -464,17 +462,25 @@ printf("\n");
 464  462                        SSLerr(SSL_F_DTLS1_PROCESS_RECORD,SSL_R_LENGTH_TOO_SHORT);
 465  463                        goto f_err;
 466  464 #else
 467     -                      goto err;
      465 +                      decryption_failed_or_bad_record_mac = 1;
 468  466 #endif
 469  467                        }
 470  468                rr->length-=mac_size;
 471  469                i=s->method->ssl3_enc->mac(s,md,0);
 472  470                if (i < 0 || memcmp(md,&(rr->data[rr->length]),mac_size) != 0)
 473  471                        {
 474     -                      goto err;
      472 +                      decryption_failed_or_bad_record_mac = 1;
 475  473                        }
 476  474                }
 477  475
      476 +      if (decryption_failed_or_bad_record_mac)
      477 +              {
      478 +              /* decryption failed, silently discard message */
      479 +              rr->length = 0;
      480 +              s->packet_length = 0;
      481 +              goto err;
      482 +              }
      483 +
 478  484        /* r->length is now just compressed */
 479  485        if (s->expand != NULL)
 480  486                {
```

OpenSSL padding oracle attack

Canvel, et al. “Password Interception in a SSL/TLS Channel.” *Crypto,* Vol. 2729. 2003.

Error-prone in practice

```
-       EVP_DigestUpdate(&md_ctx,md,2);
-       EVP_DigestUpdate(&md_ctx,rec->input,rec->length);
-       EVP_DigestFinal_ex( &md_ctx,md,NULL);
-
-       EVP_MD_CTX_copy_ex( &md_ctx,hash);
-       EVP_DigestUpdate(&md_ctx,mac_sec,md_size);
-       EVP_DigestUpdate(&md_ctx,ssl3_pad_2,npad);
-       EVP_DigestUpdate(&md_ctx,md,md_size);
-       EVP_DigestFinal_ex( &md_ctx,md,&md_size);
-
-       EVP_MD_CTX_cleanup(&md_ctx);
+       if (!send &&
+           EVP_CIPHER_CTX_mode(ssl->enc_read_ctx) == EVP_CIPH_CBC_MODE &&
+           ssl3_cbc_record_digest_supported(hash))
+               {
+               /* This is a CBC-encrypted record. We must avoid leaking any
+                * timing-side channel information about how many blocks of
+                * data we are hashing because that gives an attacker a
+                * timing-oracle. */
+
+               /* npad is, at most, 48 bytes and that's with MD5:
+                *   16 + 48 + 8 (sequence bytes) + 1 + 2 = 75.
+                *
+                * With SHA-1 (the largest hash speced for SSLv3) the hash size
+                * goes up 4, but npad goes down by 8, resulting in a smaller
+                * total size. */
+               unsigned char header[75];
+               unsigned j = 0;
+               memcpy(header+j, mac_sec, md_size);
+               j += md_size;
+               memcpy(header+j, ssl3_pad_1, npad);
+               j += npad;
+               memcpy(header+j, seq, 8);
+               j += 8;
+               header[j++] = rec->type;
+               header[j++] = rec->length >> 8;
+               header[j++] = rec->length & 0xff;
+
+               ssl3_cbc_digest_record(
+                       hash,
+                       md, &md_size,
+                       header, rec->input,
+                       rec->length + md_size, rec->orig_len,
+                       mac_sec, md_size,
+                       1 /* is SSLv3 */);
+               }
+       else
+               {
+               unsigned int md_size_u;
+               /* Chop the digest off the end :-) */
+               EVP_MD_CTX_init(&md_ctx);
+
+               EVP_MD_CTX_copy_ex( &md_ctx,hash);
+               EVP_DigestUpdate(&md_ctx,mac_sec,md_size);
+               EVP_DigestUpdate(&md_ctx,ssl3_pad_1,npad);
+               EVP_DigestUpdate(&md_ctx,seq,8);
+               rec_char=rec->type;
+               EVP_DigestUpdate(&md_ctx,&rec_char,1);
+               p=md;
+               s2n(rec->length,p);
+               EVP_DigestUpdate(&md_ctx,md,2);
+               EVP_DigestUpdate(&md_ctx,rec->input,rec->length);
```

Lucky 13 timing attack

Al Fardan and Paterson. “Lucky thirteen: Breaking the TLS and DTLS record protocols.” Oakland 2013.

Error-prone in practice

```
-       EVP_DigestUpdate(&md_ctx,md,2);
-       EVP_DigestUpdate(&md_ctx,rec->input,rec->length);
-       EVP_DigestFin
-
-       EVP_MD_CTX_co
-       EVP_DigestUpd
-       EVP_DigestUpd
-       EVP_DigestUpd
-       EVP_DigestFin
-
-       EVP_MD_CTX_cl
+       if (!send &&
+           EVP_CIPHE
+           ssl3_cbc_
+               {
+               /* Th
+                * ts
+                * da
+                * ti
+
+               /* np
+                *
+                *
+                * Wh
+                * go
+                * to
+               unsig
+               unsig
+               memcp
+               j +=
+               memcp
+               j +=
+               memcp
+               j +=
+               heade
+               heade
+               heade
+
+               ssl3_
+
+
+
+
+
+
+               }
+       else
+               {
+               unsig
+               /* Ch
+               EVP_M
+
+               EVP_M
+               EVP_D
+               EVP_D
+               EVP_D
+               rec_c
+               EVP_D
+               p=md;
+               s2n(r
+               EVP_D
+               EVP_D
```

```
-               unsigned char mac[SHA_DIGEST_LENGTH];
+               union { unsigned int  u[SHA_DIGEST_LENGTH/sizeof(unsigned int)];
+                       unsigned char c[SHA_DIGEST_LENGTH]; } mac;

                /* decrypt HMAC|padding at once */
                aesni_cbc_encrypt(in,out,len,
                                &key->ks,ctx->iv,0);

                if (plen) {     /* "TLS" mode of operation */
-                       /* figure out payload length */
-                       if (len<(size_t)(out[len-1]+1+SHA_DIGEST_LENGTH))
-                               return 0;
-
-                       len -= (out[len-1]+1+SHA_DIGEST_LENGTH);
+                       size_t inp_len, mask, j, i;
+                       unsigned int res, maxpad, pad, bitlen;
+                       int ret = 1;
+                       union { unsigned int  u[SHA_LBLOCK];
+                               unsigned char c[SHA_CBLOCK]; }
+                               *data = (void *)key->md.data;

                        if ((key->aux.tls_aad[plen-4]<<8|key->aux.tls_aad[plen-3])
-                           >= TLS1_1_VERSION) {
-                               len -= AES_BLOCK_SIZE;
+                           >= TLS1_1_VERSION)
                                iv = AES_BLOCK_SIZE;
-                       }

-                       key->aux.tls_aad[plen-2] = len>>8;
-                       key->aux.tls_aad[plen-1] = len;
+                       if (len<(iv+SHA_DIGEST_LENGTH+1))
+                               return 0;
+
+                       /* omit explicit iv */
+                       out += iv;
+                       len -= iv;
+
+                       /* figure out payload length */
+                       pad = out[len-1];
+                       maxpad = len-(SHA_DIGEST_LENGTH+1);
+                       maxpad |= (255-maxpad)>>(sizeof(maxpad)*8-8);
+                       maxpad &= 255;
+
+                       inp_len = len - (SHA_DIGEST_LENGTH+pad+1);
+                       mask = (0-((inp_len-len)>>(sizeof(inp_len)*8-1)));
+                       inp_len &= mask;
+                       ret &= (int)mask;

-                       /* calculate HMAC and verify it */
+                       key->aux.tls_aad[plen-2] = inp_len>>8;
+                       key->aux.tls_aad[plen-1] = inp_len;
+
+                       /* calculate HMAC */
                        key->md = key->head;
                        SHA1_Update(&key->md,key->aux.tls_aad,plen);
-                       SHA1_Update(&key->md,out+iv,len);
-                       SHA1_Final(mac,&key->md);

+#if 1
+                       len -= SHA_DIGEST_LENGTH;               /* amend mac */
+                       if (len>=(256+SHA_CBLOCK)) {
+                               j = (len-(256+SHA_CBLOCK))&(0-SHA_CBLOCK);
+                               j += SHA_CBLOCK-key->md.num;
```

Further refinements

Decryption path has no more measurable timing differences

Error-prone in practice

```
-       EVP_DigestUpdate(&md_ctx,md,2);
-       EVP_DigestUpdate(&md_ctx,rec->input,rec->length);
-       EVP_DigestFin
-
-       EVP_MD_CTX_co
-       EVP_DigestUpd
-       EVP_DigestUpd
-       EVP_DigestUpd
-       EVP_DigestFin
-
-       EVP_MD_CTX_cl
+       if (!send &&
+           EVP_CIPHE
+           ssl3_cbc_
+               {
+               /* Th
+                * ts
+                * da
+                * ti
+
+               /* np
+                *
+                *
+                * Wh
+                * go
+                * to
+               unsig
+               unsig
+               memcp
+               j +=
+               memcp
+               j +=
+               memcp
+               j +=
+               heade
+               heade
+               heade
+
+               ssl3_
+
+
+
+
+
+
+               }
+       else
+               {
+               unsig
+               /* Ch
+               EVP_M
+
+               EVP_M
+               EVP_D
+               EVP_D
+               EVP_D
+               rec_c
+               EVP_D
+               p=md;
+               s2n(r
+               EVP_D
+               EVP_D
```

```
-               unsigned char mac[SHA_DIGEST_LENGTH];
+               union { unsigned int  u[SHA_DIGEST_LENGTH/sizeof(unsigned int)];
+                       unsigned char c[SHA_DIGEST_LENGTH]; } mac;

                /* decrypt HMAC|padding at once */
                aesni_cbc_encrypt(in,out,len,
                                &key->ks,ctx->iv,0);

                if (plen) {     /* "TLS" mode of operation */
-                       /* figure out payload length */
-                       if (len<(size_t)(out[len-1]+1+SHA_DIGEST_LENGTH))
-                               return 0;
-
-                       len -= (out[len-1]+1+SHA_DIGEST_LENGTH);
+                       size_t inp_len, mask, j, i;
+                       unsigned int res, maxpad, pad, bitlen;
+                       int ret = 1;
+                       union { unsigned int  u[SHA_LBLOCK];
+                               unsigned char c[SHA_CBLOCK]; }
+                               *data = (void *)key->md.data;

                        if ((key->aux.tls_aad[plen-4]<<8|key->aux.tls_aad[plen-3])
-                           >= TLS1_1_VERSION) {
-                               len -= AES_BLOCK_SIZE;
+                           >= TLS1_1_VERSION)
                                iv = AES_BLOCK_SIZE;
-                       }

-                       key->aux.tls_aad[plen-2] = len>>8;
-                       key->aux.tls_aad[plen-1] = len;
+                       if (len<(iv+SHA_DIGEST_LENGTH+1))
+                               return 0;
+
+                       /* omit explicit iv */
+                       out += iv;
+                       len -= iv;
+
+                       /* figure out payload length */
+                       pad = out[len-1];
+                       maxpad = len-(SHA_DIGEST_LENGTH+1);
+                       maxpad |= (255-maxpad)>>(sizeof(maxpad)*8-8);
+                       maxpad &= 255;
+
+                       inp_len = len - (SHA_DIGEST_LENGTH+pad+1);
+                       mask = (0-((inp_len-len)>>(sizeof(inp_len)*8-1)));
+                       inp_len &= mask;
+                       ret &= (int)mask;

-                       /* calculate HMAC and verify it */
+                       key->aux.tls_aad[plen-2] = inp_len>>8;
+                       key->aux.tls_aad[plen-1] = inp_len;
+
+                       /* calculate HMAC */
                        key->md = key->head;
                        SHA1_Update(&key->md,key->aux.tls_aad,plen);
-                       SHA1_Update(&key->md,out+iv,len);
-                       SHA1_Final(mac,&key->md);

+#if 1
+                       len -= SHA_DIGEST_LENGTH;               /* amend mac */
+                       if (len>=(256+SHA_CBLOCK)) {
+                               j = (len-(256+SHA_CBLOCK))&(0-SHA_CBLOCK);
+                               j += SHA_CBLOCK-key->md.num;
```

Further refinements

Decryption path has no more measurable timing differences

Error-prone in practice

```
583   584          maxpad |= (255 - maxpad) >> (sizeof(maxpad) * 8 - 8);
584   585          maxpad &= 255;
585   586
      587    +     ret &= constant_time_ge(maxpad, pad);
      588    +
586   589          inp_len = len - (SHA_DIGEST_LENGTH + pad + 1);
587   590          mask = (0 - ((inp_len - len) >> (sizeof(inp_len) * 8 - 1)));
588   591          inp_len &= mask;
```

CVE-2016-2107

Somorovsky. “Curious padding oracle in OpenSSL.”

Writing constant-time code is hard

- **Challenge**: manually ensuring code is CT
  - Standard programming constructs introduce timing leaks
  - Manually keep track of secret vs. public

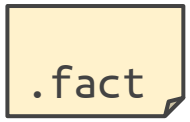
- **Consequence**: vulnerabilities!
  - Difficult to write correct code
  - Hard to understand what CT code is doing
  - Hard to maintain CT code

This is what DSLs are for!

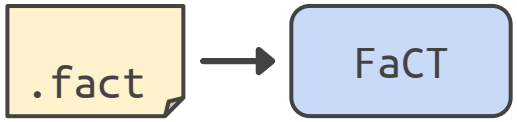
- Explicitly distinguish secret vs. public values
- Type system to prevent writing leaky code
- Compiler to transform high-level constructs to CT

FaCT

FaCT



FaCT



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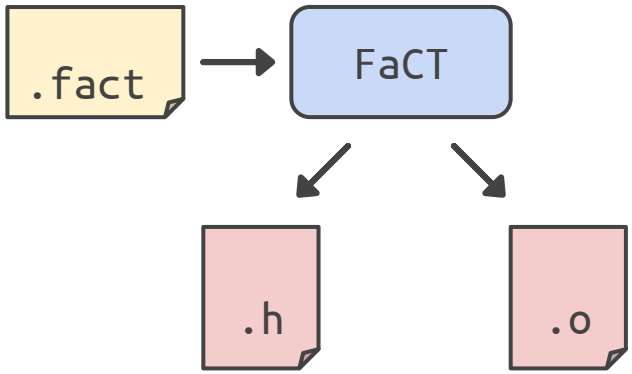

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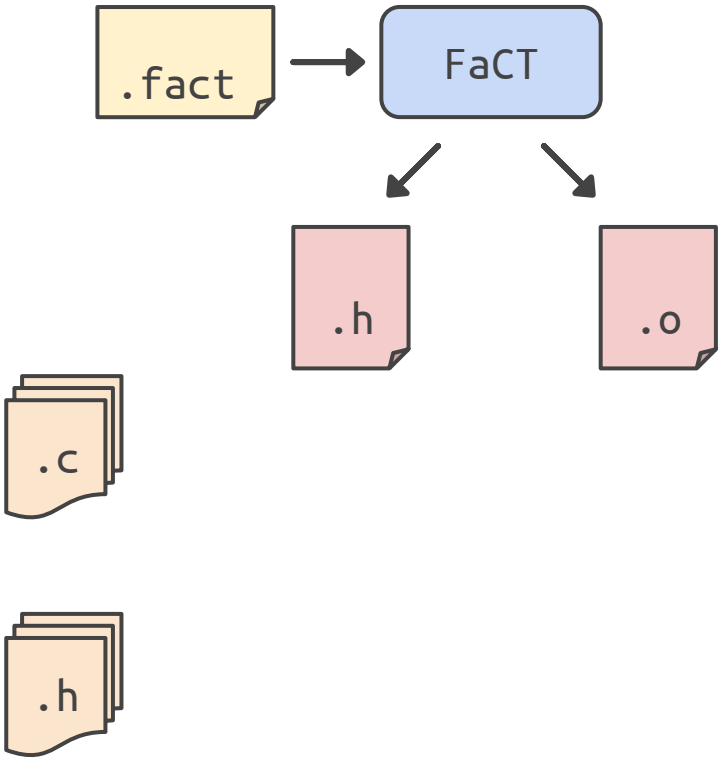

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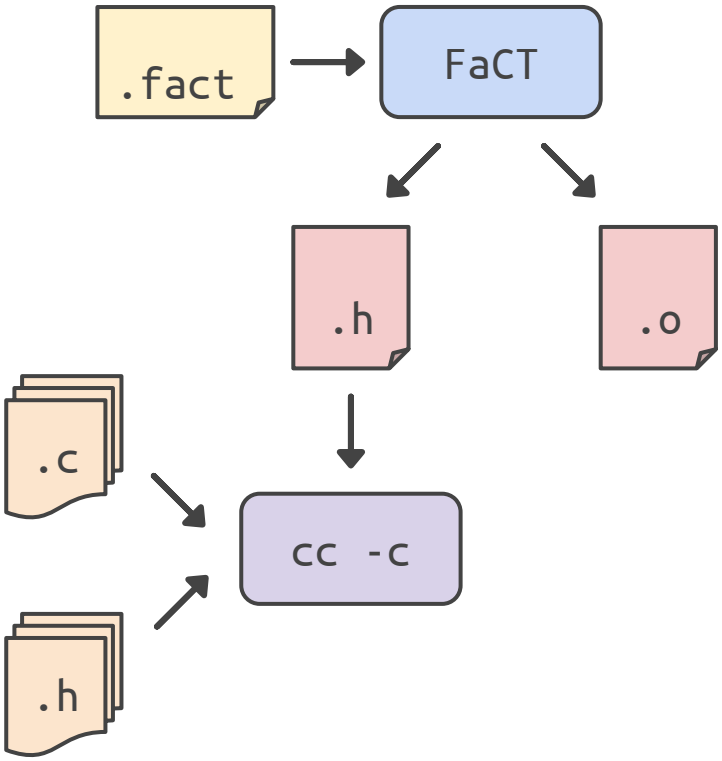

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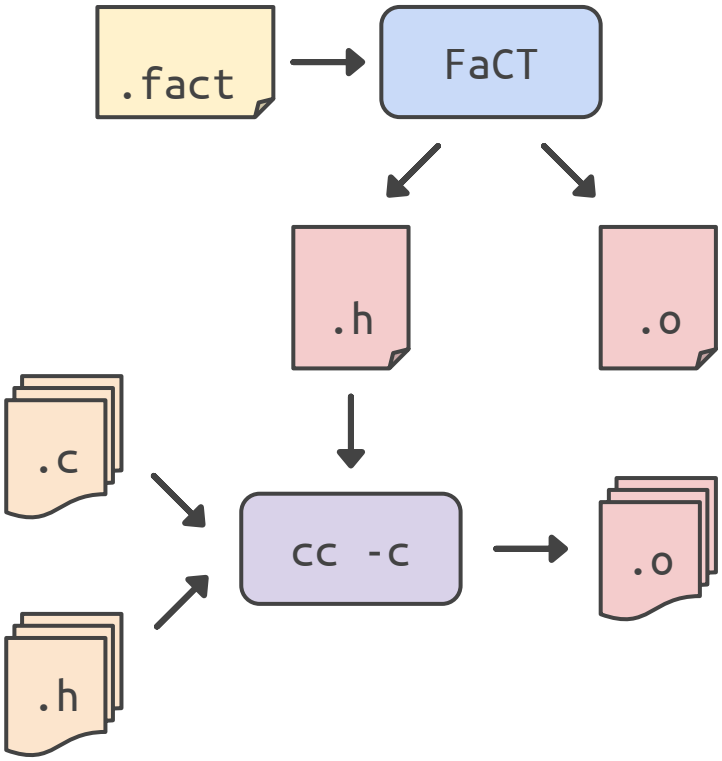

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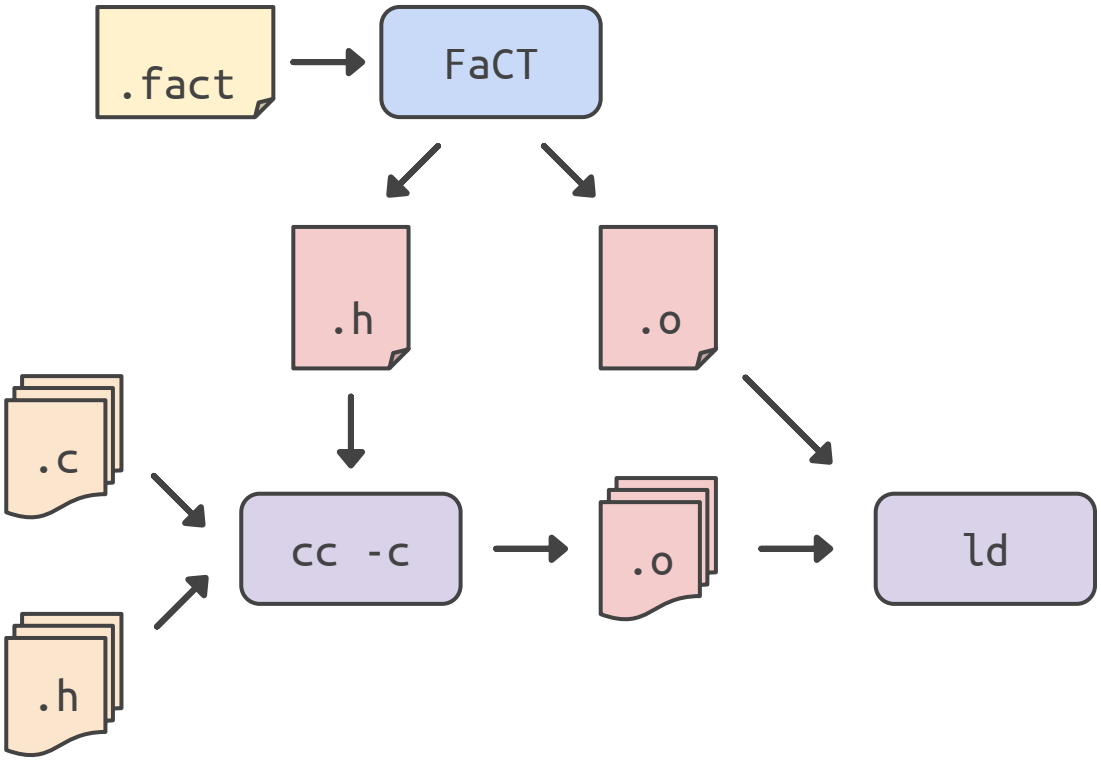

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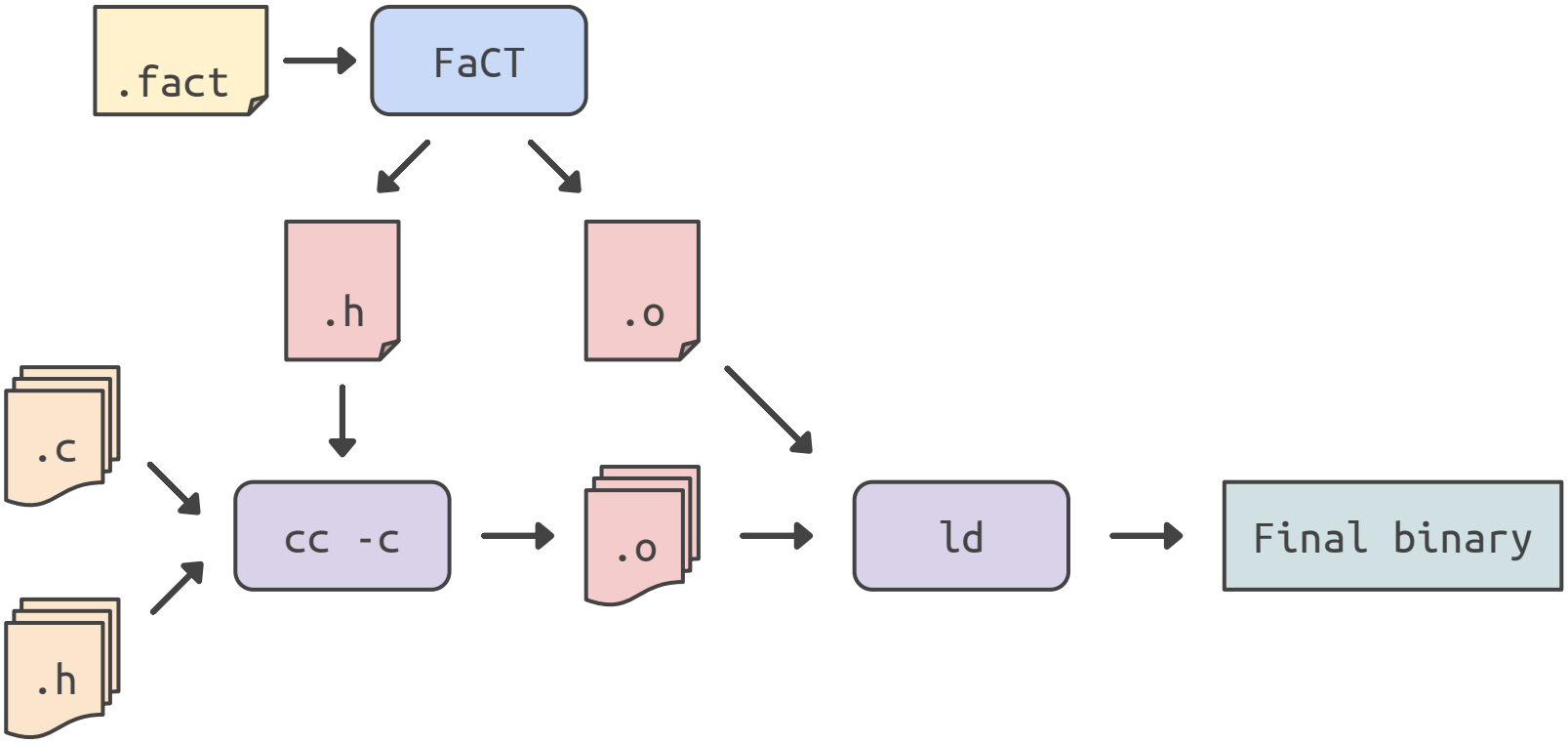

What does FaCT look like?

```
secret int32 remove_padding(secret mut uint8[] buf) {
  assume(len buf >= 255);
  secret uint8 padlen = buf[len buf - 1];
  for (uint64 i from len buf - 255 to len buf) {
    if (i >= len buf - padlen) {
      if (buf[i] != padlen) {
        return -1;
      }
      buf[i] = 0;
    }
  }
  return int32(padlen);
}
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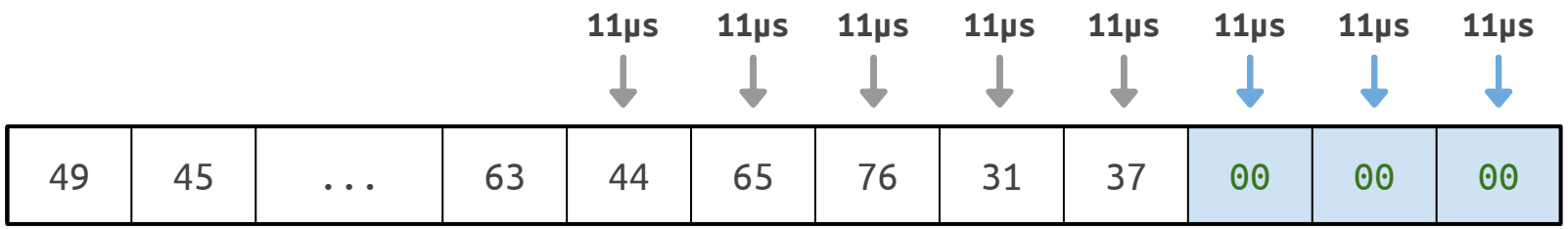
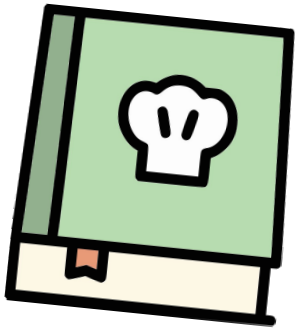


Automatically transform code



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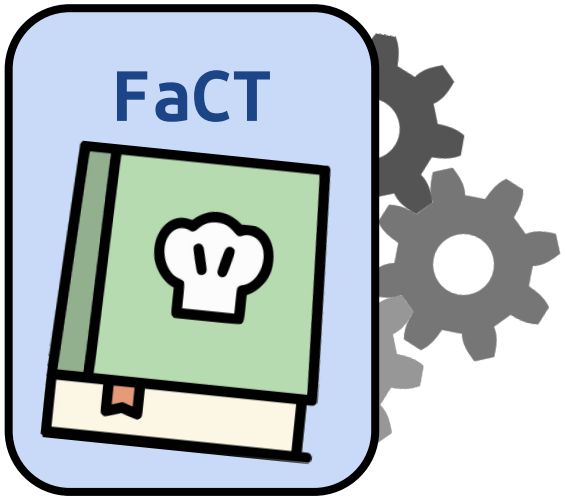

Automatically transform code

- Transform secret branches into straight-line code
- Keep track of static control flow

```
if (s) {
    if (s2) {
        x = 42;
    } else {
        x = 17;
    }
    y = x + 2;
}
```

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    if (s2) {
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    }
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```

```
x = ct_select(s & s2, 42, x);
x = ct_select(s & ~s2, 17, x);
y = ct_select(s, x + 2, y);
```

Automatically transform code

- Transform away early returns
- Keep track of current return state

```
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```

Automatically transform code

- Transform away early returns
- Keep track of current return state

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if (s) {
    return 42;
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return 17;
```

```
rval = ct_select(s & ~returned, 42, rval);
returned |= s;

rval = ct_select(~returned, 17, rval);
returned |= true;

      ⋮

return rval;
```

Automatically transform code

- Transform function side effects
  - Depends on control flow state of caller
- Pass the current control flow as an extra parameter

```
void fn(mut x) {
    x = 42;
}


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    fn(ref x);
}
```

Automatically transform code

- Transform function side effects
  - Depends on control flow state of caller
- Pass the current control flow as an extra parameter

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void fn(mut x) {
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}
```

```
void fn(mut x, bool state) {
    x = ct_select(state, 42, x);
}
```

```
if (s) {
    fn(ref x);
}
```

```
fn(ref x, s);
```

Labels ensure no leakage

- No assignment from `secret` to `public`
- Type system tracks control flow label
  - Only transform secret control flow
- Prevent secret expressions we can’t transform:

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```
for (uint32 i from 0 to secret_value) {
    do_operation();
}
```

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```
for (uint32 i from 0 to public_value) {
    if (i < secret_value) {
        do_operation();
    }
}
```

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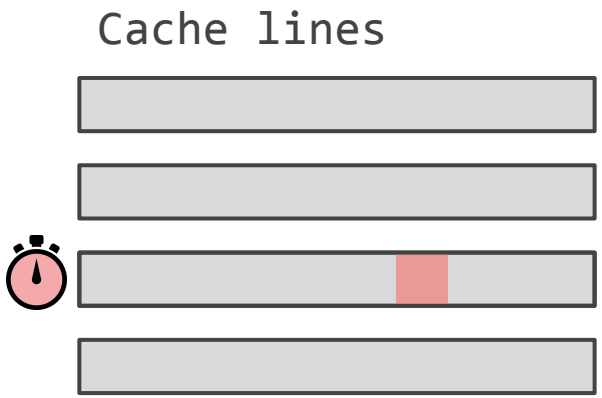
  - Array indices

```
x = sensitive_buffer[secret_value];
```



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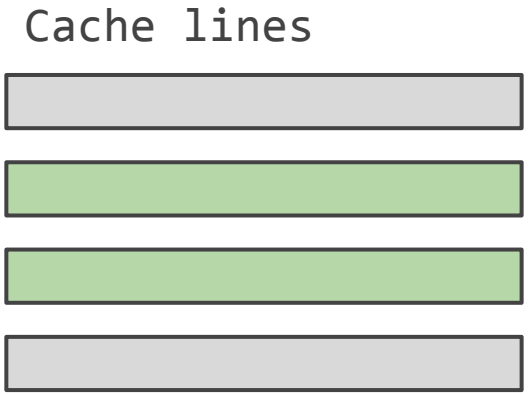
```
for (uint32 i from public_lo to public_hi) {
    if (i == secret_value) {
        x = sensitive_buffer[i];
    }
}
```



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  - Variable-time instructions

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x = public_value / secret_value2;
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```
x = public_value / public_value2;
```

OR

```
x = ct_div(public_value, secret_value2);
```

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- Prevent secret expressions we can't transform:
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  - Array indices
  - Variable-time instructions
  - Recursive calls

```
secret uint32 fact(secret uint32 n) {
  if (n > 1) {
    return n * fact(n - 1);
  }
  return 1;
}
```

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buf[31] = ct_select(m, 0, buf[31]);
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  - Similar problem for secret early return

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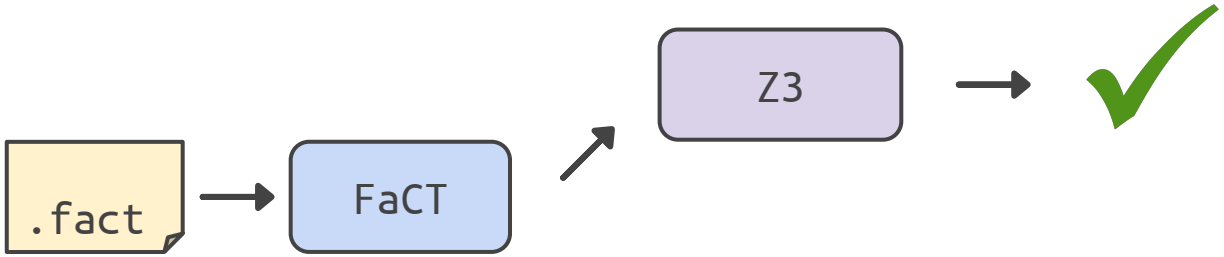
- **Problem:** secret if-statements always perform branches
  - Does not guard execution
  - Similar problem for secret early return
- **Solution:** disallow these programs!

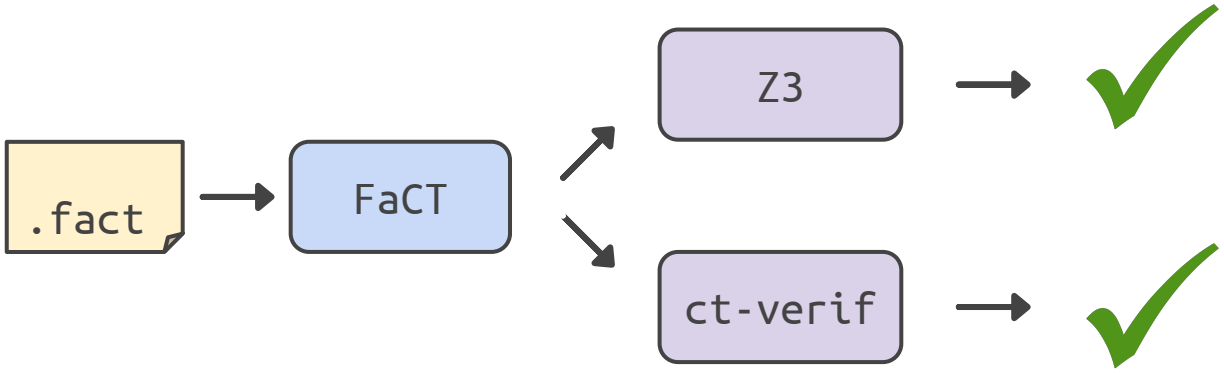
Verifying constant-time code

- FaCT is memory safe and has no undefined behavior
  - Generate constraints while type checking
  - Aware of secret-if semantics



Verifying constant-time code

- FaCT is memory safe and has no undefined behavior
  - Generate constraints while type checking
  - Aware of secret-if semantics
- FaCT generates constant-time code
  - Verified with external tool



Ok, but how good is it really?

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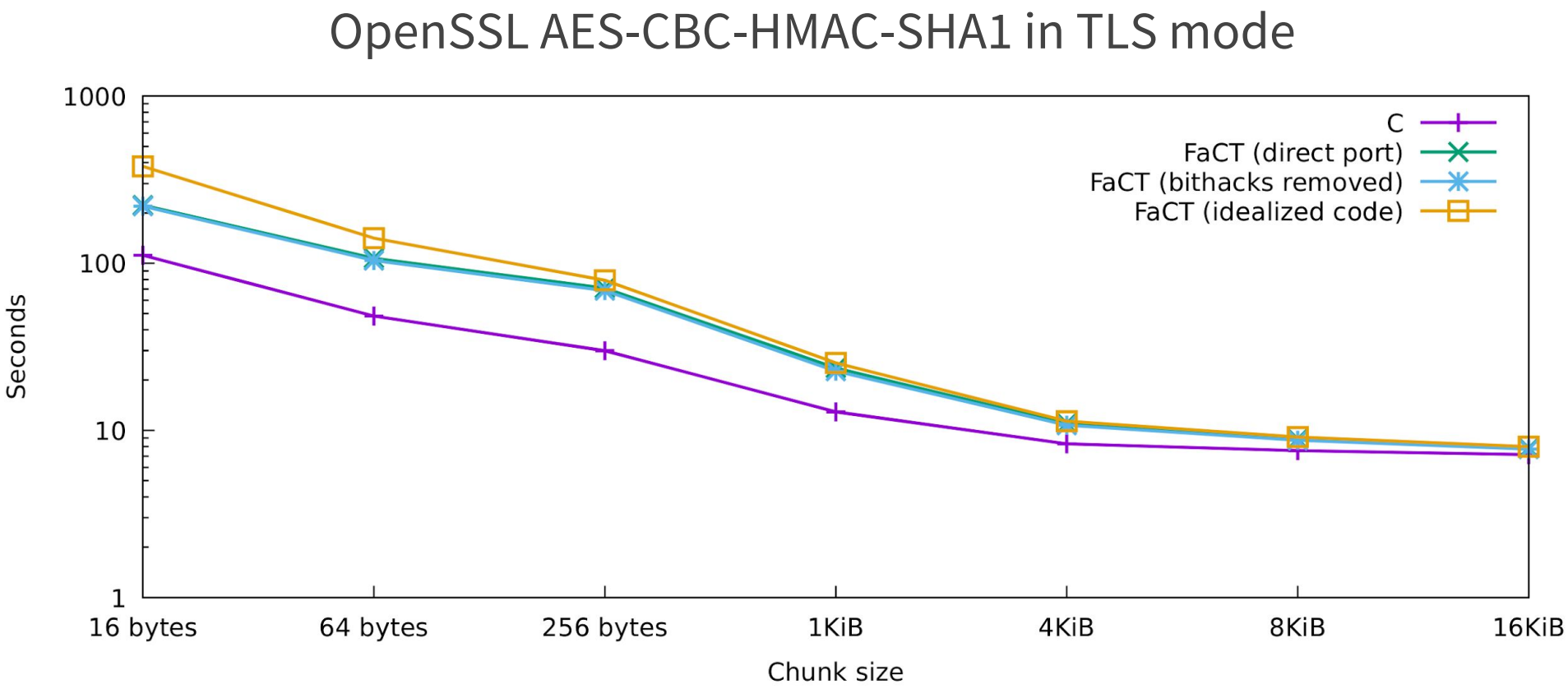
- How fast is it?
- How usable is it?

- Case studies:
  - libsodium's crypto_secretbox
  - OpenSSL's AES-CBC-HMAC-SHA1
  - mbedTLS's Montgomery multiplication & sliding window exponentiation
  - DJB/Langley's curve-25519

Performance numbers



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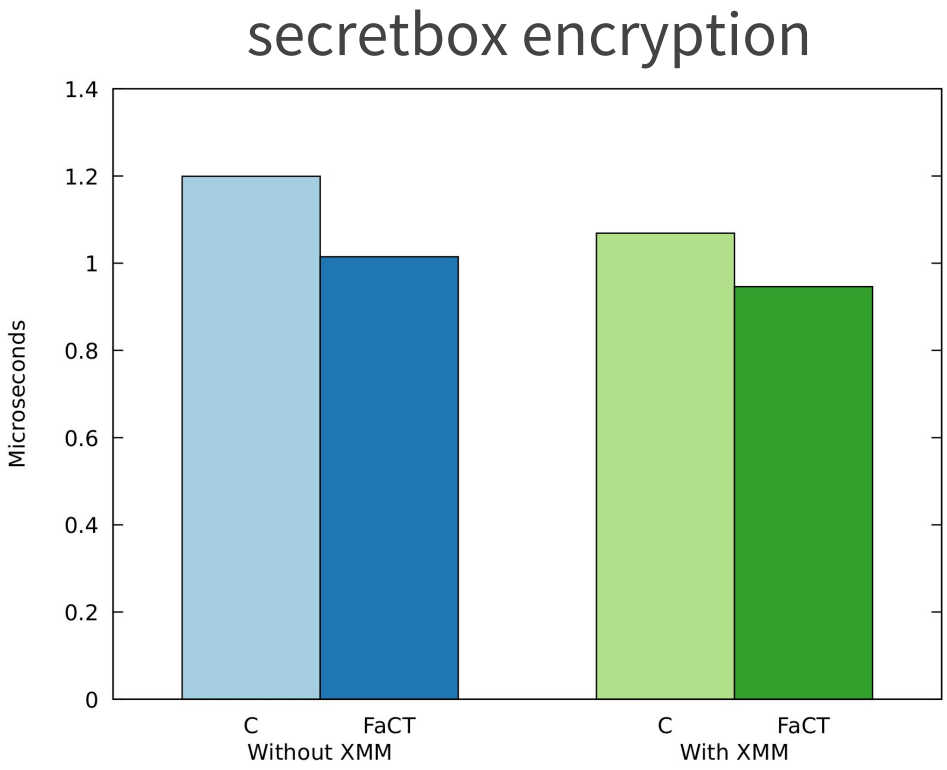

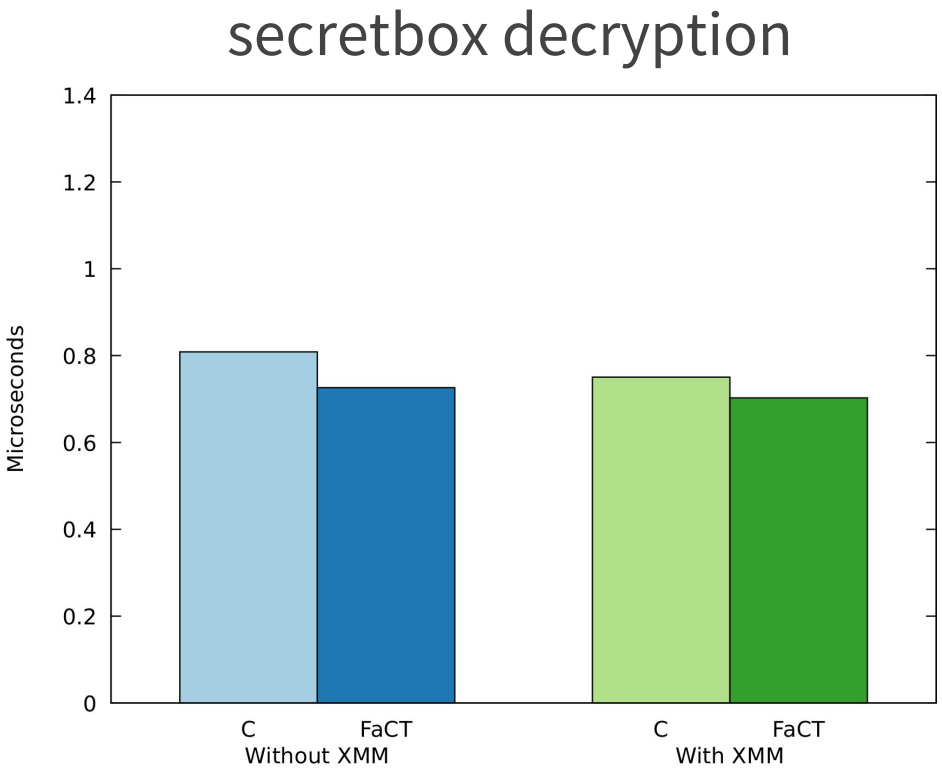

Future directions

- Optimize transformations
- Add other backends (ARM, CT-WASM, ...)
- Verify the FaCT compiler

FaCT https://github.com/PLSysSec/FaCT

- DSL for cryptographic code
- Automatic transformation to constant-time
- Easily fits into your existing toolchain
- Usable and fast