Software Interfaces to Cryptographic Primitives

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Overview

- Introduction
- Cryptographic Primitives
- Cryptographic API's
- Key Management Issues
- Conclusion

Introduction

- Security = prevention and detection of unauthorized actions on information
- Two important cases:
  - An attacker has access to the raw bits representing the information
=> need for cryptographic techniques
  - There is a software layer between the attacker and the information
=> access control techniques

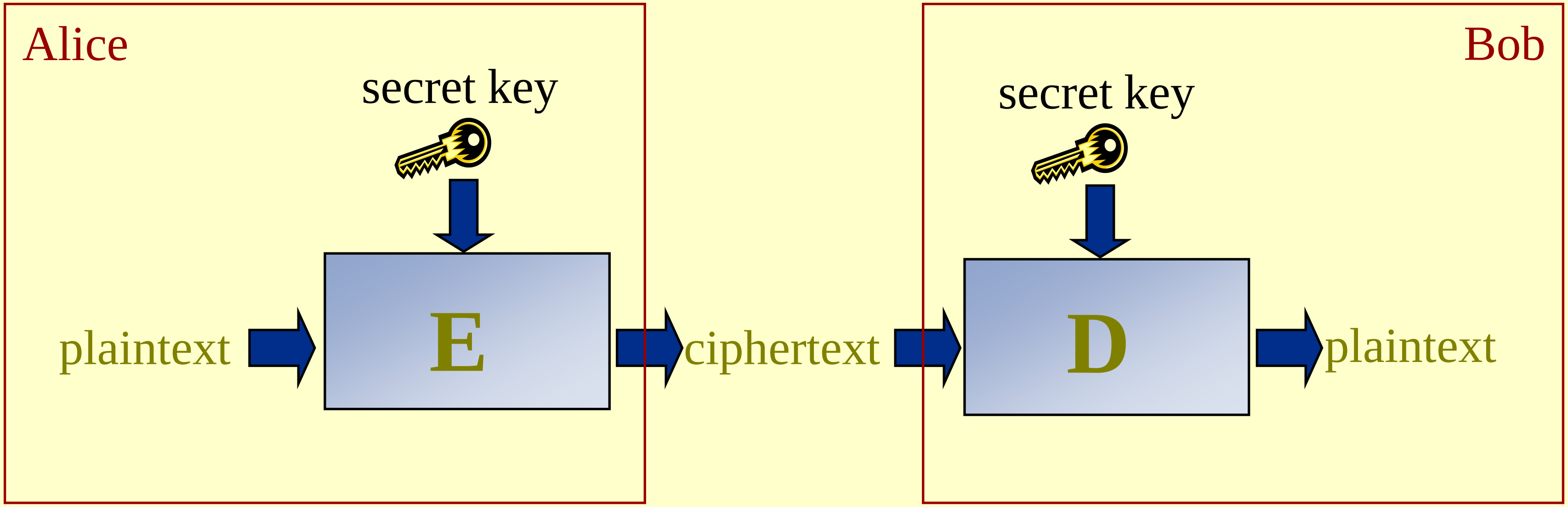
Introduction

- Cryptography builds on algorithms (**primitives**) that guarantee specific information security related security properties
  - E.g. Hash functions, symmetric encryption, ...
  - Precisely specifying the security properties of most primitives is intricate
- To guarantee interesting, more high-level, security properties, primitives are used in cryptographic **protocols**
  - E.g. Secure communication, entity authentication, ...

Cryptographic Primitives

- Symmetric cryptography
- Public-key cryptography
- Hash functions
  - Unkeyed hash functions
  - Message Authentication Codes (MAC's)
- Digital signatures
- Secure random numbers

Symmetric Cryptography



- NOTE: Algorithm secrecy ↔ key secrecy

Cryptanalytic Attacks

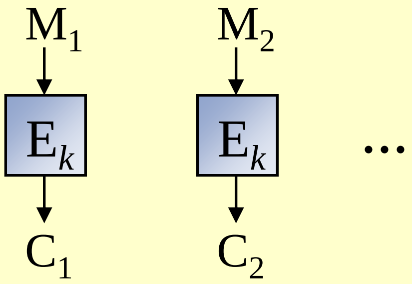
- Algorithm should be secure against
  - Ciphertext-only attack
    - Find *k* or plaintext given only ciphertext.
  - Known-plaintext attack
    - Find *k* given ⟨M_1, C_1⟩, ⟨M_2, C_2⟩, ...
  - Chosen-plaintext attack
    - Known-plaintext, but adversary chooses M_1, M_2, ...
  - Chosen-ciphertext
    - Known-plaintext, but adversary chooses C_1, C_2, ...
- Security depends on:
  - Algorithm: use well-known algorithms
  - Key-length: longer keys improve security

Block ciphers and stream ciphers

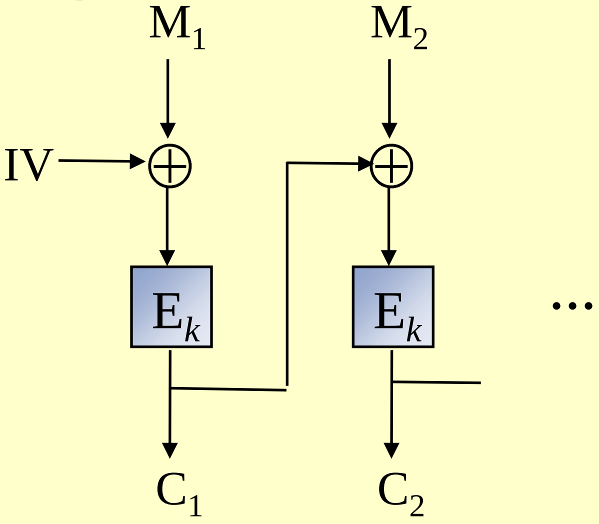
- Block ciphers encrypt fixed-size input blocks
  - *Padding* may be necessary.
    - E.g. PKCS#7 padding
  - Different *modes* of operation on arbitrary sized streams (see next slide)
  - Block size influences security of the cipher
- Stream ciphers can encrypt bit-by-bit
  - E.g. one-time-pad
  - Key stream generators

Encryption modes (block ciphers)

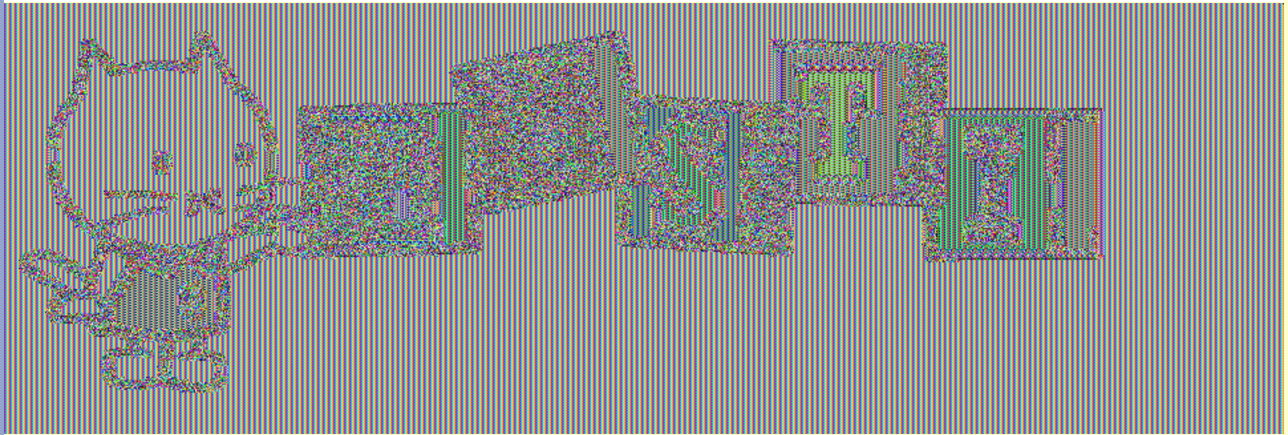
- Electronic Codebook (ECB)



- Cipher Block Chaining (CBC)



Cleartext



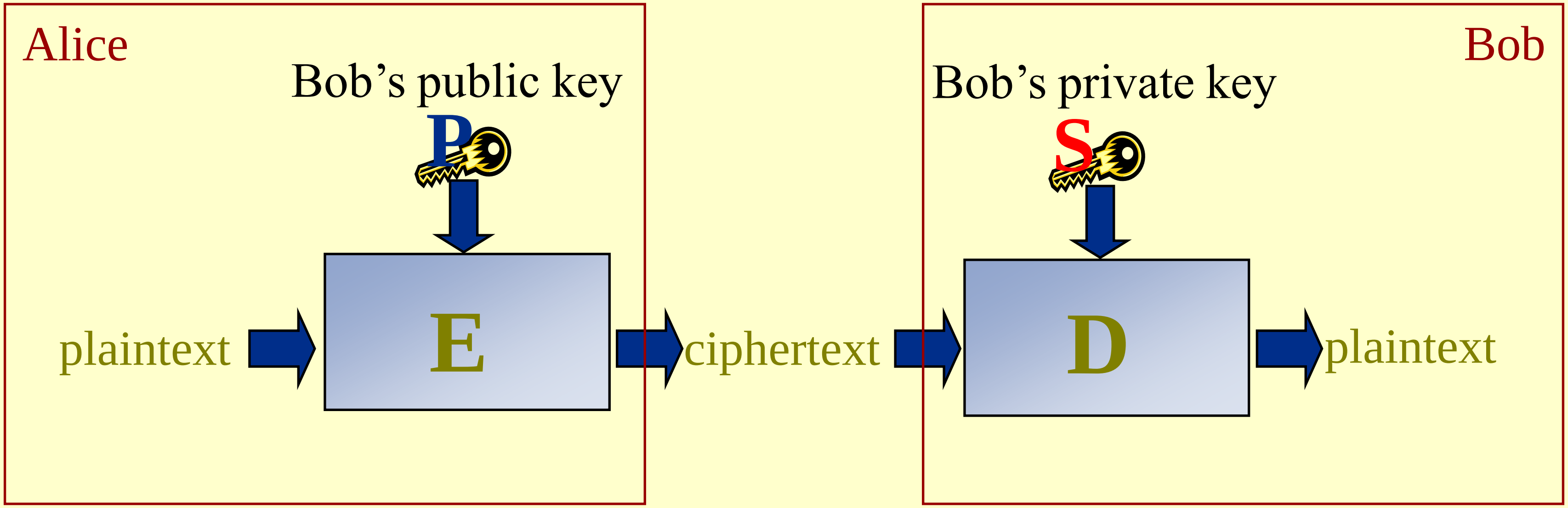
DES / ECB

DES / CBC

Real-world Algorithms

- DES (Data Encryption Standard)
  - Designed by IBM in 1970’s, influenced by NSA
  - 64-bit blocks, 56-bit key (too short nowadays)
- Triple DES
  - Three DES encryptions with independent keys
- AES (Advanced Encryption Standard) / Rijndael
  - Made in Belgium
  - Variable key/block length; standards 128, 192 or 256 bits
- RC4
  - Proprietary stream cipher of RSA Labs

Public-key Cryptography



- Key generation algorithm
- Should be secure against the same attacks as symmetric encryption
- Easier key management (see later) but slower

Public-key Cryptography

- Public-key ciphers are all block ciphers
  - Block size is much larger than for symmetric ciphers
  - Typically only single block encryption to encrypt a symmetric key
  - Padding is more elaborate to deal with small message space attacks
    - *Randomization* of the plaintext

Real-world Algorithms

- RSA (Rivest, Shamir, Adleman)
  - Widely used: de facto standard for public-key cryptography
  - Variable key length
  - Based on problem of factoring large integers
- ECC (Elliptic Curve Cryptography)
  - For wireless and embedded environments
- Others exist but not frequently used
  - e.g. Rabin, ElGamal, ...
- Padding algorithms
  - PKCS#1 v1.5
  - OAEP

Notational Conventions

- Notation for keys:
  - Symmetric key: K, K_{AB} 
  - A's public key: PK_A 

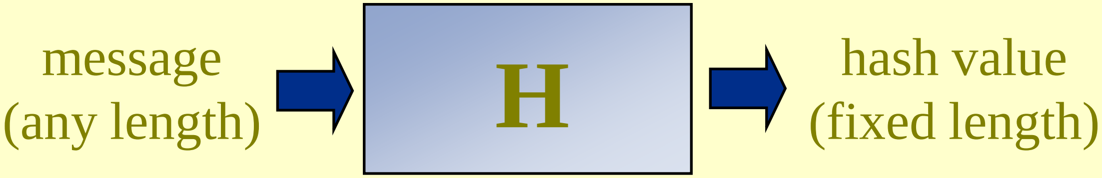
  - A's private key: SK_A 

- Notation for encryption:
  - ciphertext = {plaintext}K
  - ciphertext = {plaintext}PK

Hash Functions

- Definition
  - Maps arbitrary strings on fixed-length hash values
  - "Fingerprint" of message
  - AKA *Message Digest*
- Cryptographic hash functions are:
  - One way
  - Collision resistant
- Two flavours: keyed (MAC's) and unkeyed

Unkeyed Hash Functions



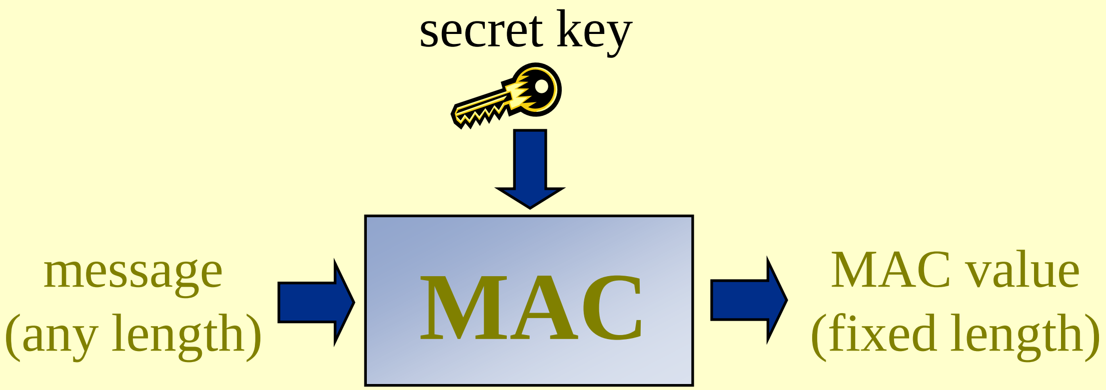
message
(any length)

H

hash value
(fixed length)

- One way:
  - Easy to compute hash value for message
  - Hard to find message with specific hash value
- Collision resistant:
  - Hard to find second message with same hash value
- Used for detecting unauthorized changes
  - e.g. Detection of virus infection

Message Authentication Codes


secret key

message
(any length)

MAC

MAC value
(fixed length)

- Properties:
  - One way
  - Collision resistant
  - Protected by secret key:
    - Computing and checking impossible without key
- Used for message integrity check

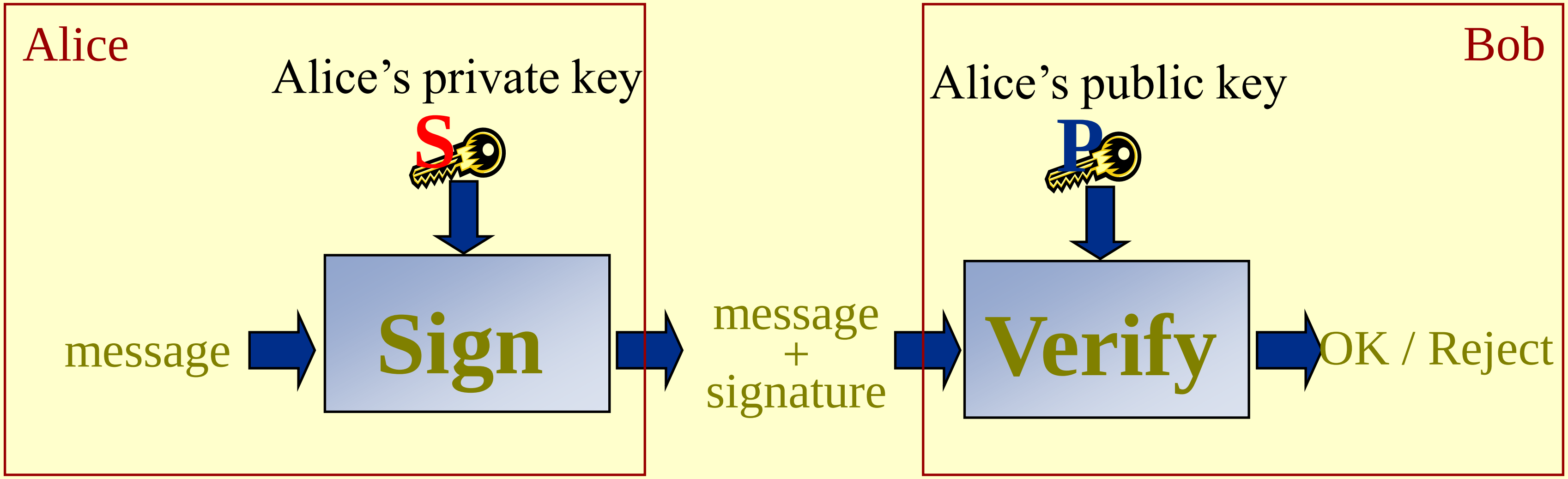
Real-world Algorithms

- Unkeyed hash functions:
  - SHA-1 (Secure Hash Algorithm)
    - Designed by NSA
    - Arbitrary-length input → 160-bit output
    - Known attacks -> now considered insecure
  - MD-5 (Message Digest)
    - By Ron Rivest
    - Arbitrary-length input → 128-bit output
    - Known attacks -> now considered insecure
  - SHA-2 / 256 and SHA-2 / 512

Real-world Algorithms

- MAC's:
  - Any symmetric encryption of any hash function
  - Using only hash functions: $\mathrm{MAC}_k(M) = \mathrm{H}(k,M)$, or better: H-MAC turns any unkeyed hash in a MAC
  - DES-CBC-MAC: the last block of a CBC encryption

Digital Signatures



- Key generation algorithm
- Digital signatures provide:
  - Message origin authentication
  - Non repudiation

Digital Signatures

- Digital signatures also operate on fixed size input blocks
  - Padding is necessary but has completely different requirements than padding for encryption
    - E.g. no randomization
  - To sign arbitrary sized messages
    - Sign a hash of the message
- Standardized signature schemes specify how hashing and padding must be used

Real-world Algorithms

- RSA
  - Public key and private key are interchangeable
  - Signature = encryption with private key
  - Verification = decryption with public key
- DSA (Digital Signature Algorithm)
  - Designed by NSA
  - Key length from 512 to 1024 bits
- Elliptic curve variant of DSA (ECDSA)

Notational Conventions

- MAC's:
  - MAC value = [message]K
- Digital Signatures:
  - signature = [message]SK

Secure Random Numbers

- True randomness is slow to obtain:
  - physical processes: noise diode, coin tosses, …
  - timing user interface events
- Solution: Pseudo-Random Generators
  - John von Neumann: "*Anyone who considers arithmetical methods of producing random digits is, of course, in a state of sin*"
  - generate many (seemingly) random numbers starting from one seed

Secure Random Numbers

- Importance of random number generation:
  - Generating cryptographic keys
  - Generating “challenges” in cryptographic protocols
- Cryptographically secure randomness
  - Passes all statistical tests of randomness
  - Impossible to predict next bit from previous output bits
- Do not use a built-in random generator that uses an unknown algorithm!

Conclusions

- Designing cryptographic primitives is *extremely hard*
  - never try to design your own algorithms, use well-known algorithms
- Implementing cryptographic primitives is *extremely hard*
  - whenever possible, use a crypto library or API from a reputable vendor

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Cryptographic API’s

- Design principles of modern API’s:
  - Cryptographic Service Providers (CSP’s) and cryptographic frameworks
- The Java Cryptography Architecture and Extensions (JCA/JCE)
- The .NET cryptographic library
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Design principles

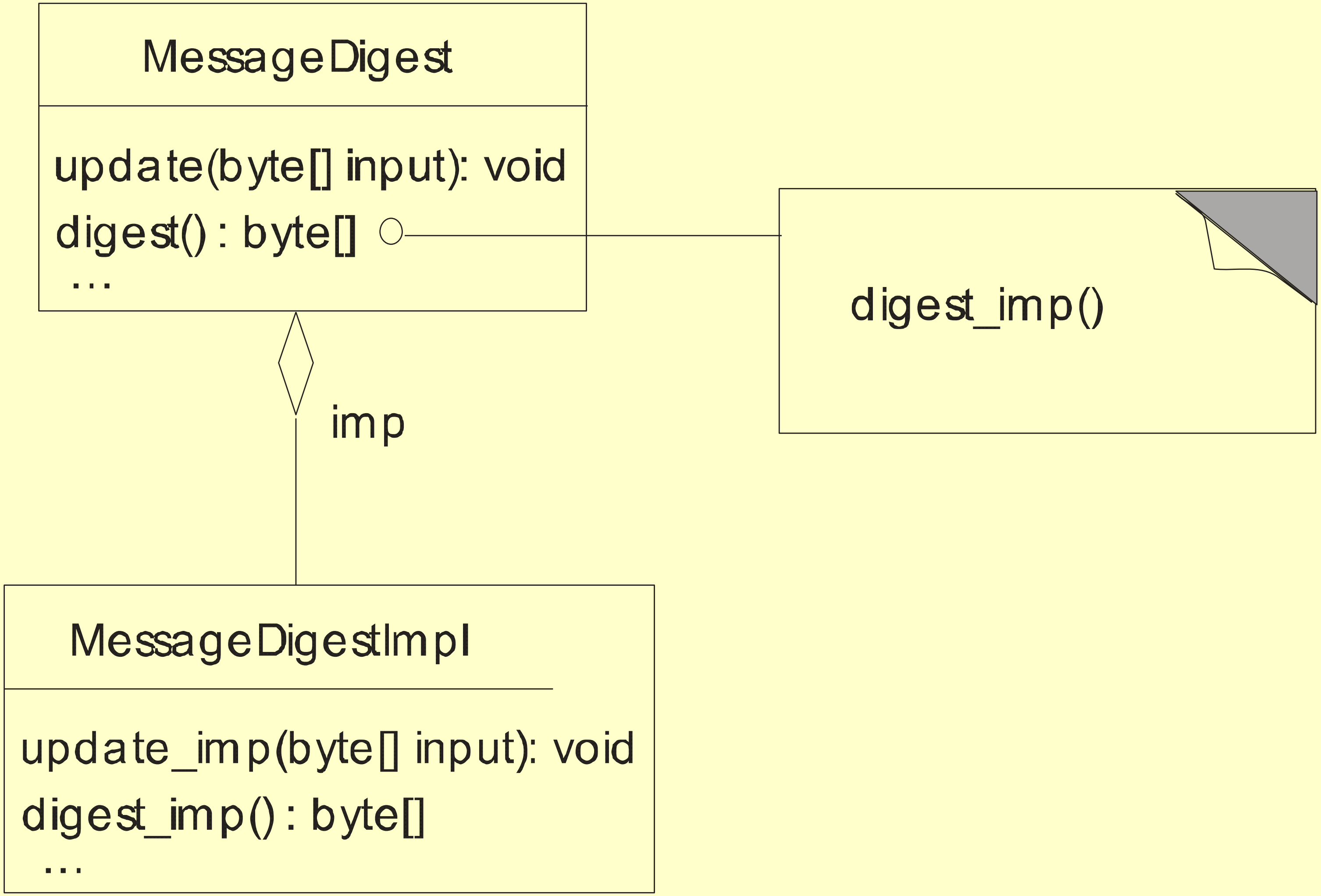
- Algorithm independence
  - *Engine* classes
- Implementation independence
  - *Provider* based architecture
- Implementation interoperability
  - *Transparent* and *opaque* data types

Bottom line: security mechanisms should be easy to change over time

Engine classes

- Abstraction for a cryptographic service
  - Provide cryptographic operations
  - Generate/supply cryptographic material
  - Generate objects encapsulating cryptographic keys
- Define the Cryptographic API
- Bridge pattern or inheritance hierarchy to allow for implementation independence
- Instances created by factory method

Bridge pattern



MessageDigest

update(byte[] input): void

digest() : byte[]

…

digest_imp()

imp

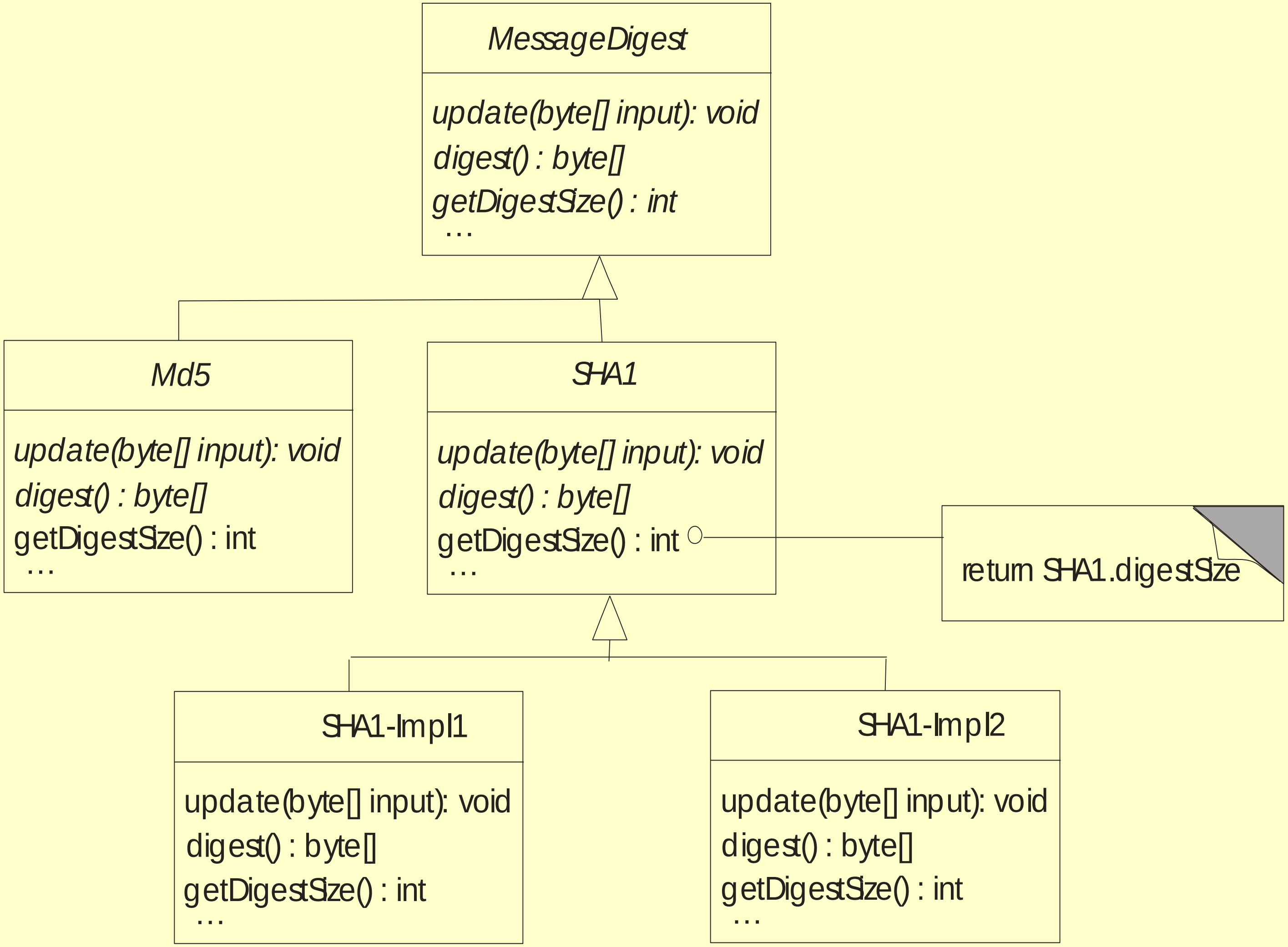
MessageDigestImpl

update_imp(byte[] input): void

digest_imp() : byte[]

…

Inheritance based decoupling



Opaque vs transparent data

- Representation of data items like keys, algorithm parameters, initialization vectors:
  - Opaque: chosen by the implementation object
  - Transparent: chosen by the designer of the cryptographic API
- Transparent data allow for implementation interoperability
- Opaque data allow for efficiency or hardware implementation

Crypto frameworks and CSP's

- A *cryptographic framework* defines:
  - Engine classes (and possibly algorithm classes)
  - Transparent key and parameter classes
  - Interfaces for opaque keys and parameters
- A *cryptographic service provider* defines:
  - Implementation classes
  - Opaque key and parameter classes
  - Possibly methods to convert between opaque and transparent data

Cryptographic API's

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The JCA/JCE

- Java Crypto API structured as a cryptographic framework with CSP’s
- Split in:
  - The *Java Cryptography Architecure (JCA)*
  - The *Java Cryptography Extensions (JCE)*
- This split is because of US export-control regulations for cryptography

US Export Restrictions

- US consider crypto software as munitions
  - → export controls
  - → no internal or import controls
- Before January 2000
  - Export of strong encryption products (> 40 bits) forbidden
    - Download is form of export!
  - No restrictions on authentication products
- Since January 2000: relaxed
  - Exception License needed for export
    - Received after technical review by NSA
  - Still forbidden to “Terrorist-7” countries

Engine classes (JCA)

java.security.*

- MessageDigest

  hash functions
- Signature
- SecureRandom
- KeyPairGenerator

  generate new key pairs
- KeyFactory

  convert existing keys
- CertificateFactory

  generate certificates from encoded form
- KeyStore

  database of keys
- AlgorithmParameters
- AlgorithmParameter-Generator

Engine classes (JCE)

`javax.crypto.*`

- Cipher
  - encryption, decryption
- Mac
- KeyGenerator
  - generate new symmetric keys
- SecretKeyFactory
  - convert existing keys
- KeyAgreement

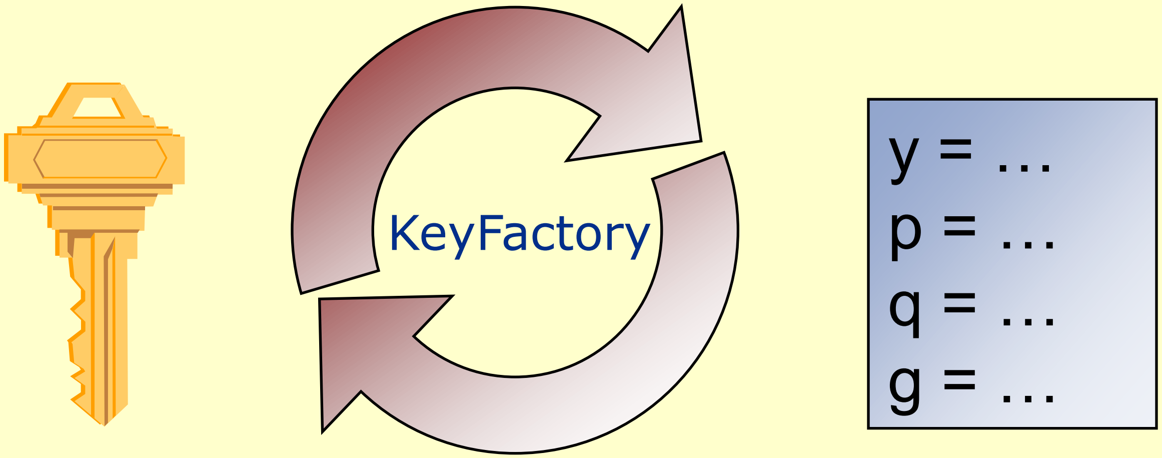
Key Classes

Opaque Representation

- No direct access to key material
- Encoded in provider-specific format
- `java.security.Key`

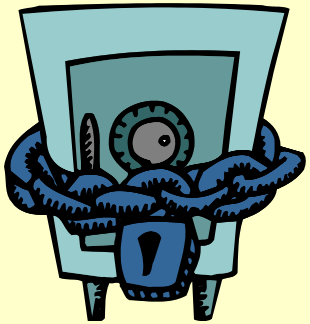
Transparent Representation

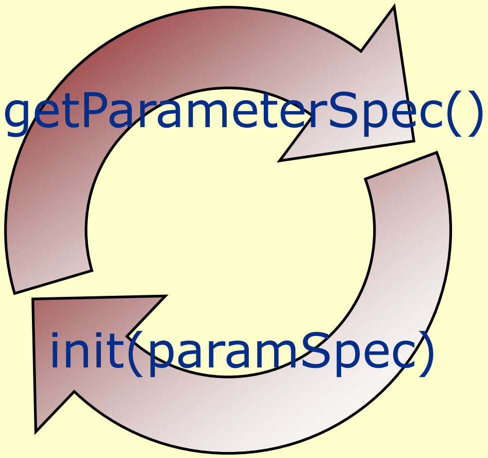
- Access each key material value individually
- Provider-independent format
- `java.security.KeySpec`



Parameter Classes

Opaque Representation	Transparent Representation
• No direct access to parameter fields	• Access each parameter value individually
• Encoded in provider-specific format	• Provider-independent format
• `AlgorithmParameters`	• `AlgorithmParameterSpec`





getParameterSpec()

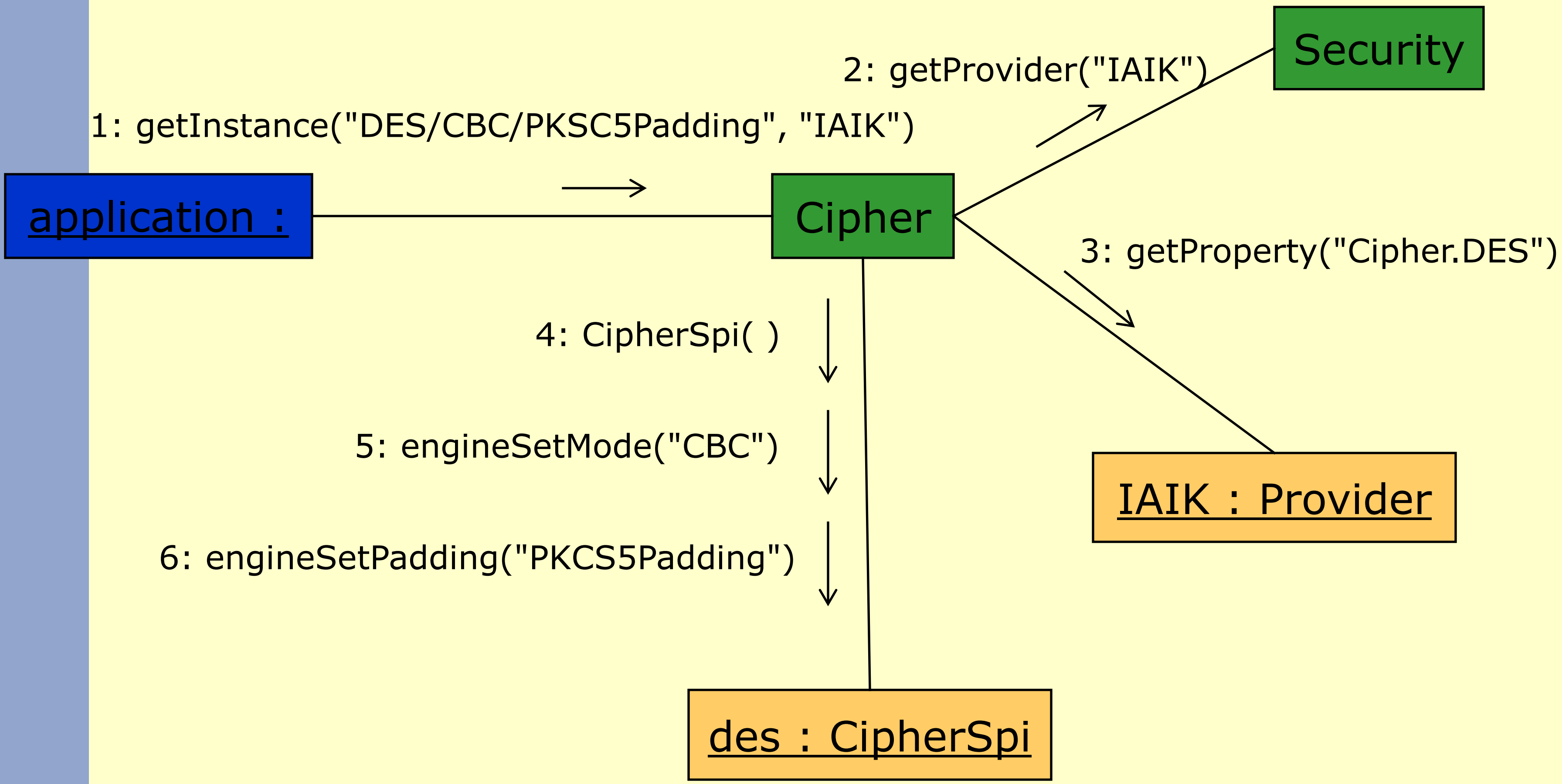
init(paramSpec)

g = …
p = …
q = …

Overall structure of the framework

- Security class encapsulates configuration information (what providers are installed)
- Per provider, an instance of the provider class contains provider specific information (e.g. what algorithms are implemented in what classes)
- Factory method on the engine class interacts with the Security class and provider objects to instantiate a correct implementation object

Example: creating ciphers



1: getInstance("DES/CBC/PKSC5Padding", "IAIK")

2: getProvider("IAIK")

3: getProperty("Cipher.DES")

4: CipherSpi( )

5: engineSetMode("CBC")

6: engineSetPadding("PKCS5Padding")

Additional support and convenience classes

- Secure streams
  - For easy bulk encryption and decryption
- Signed objects
  - Integrity checked serialized objects
- Sealed objects
  - Confidentiality protected serialized objects
- Working with certificates
- Keystores

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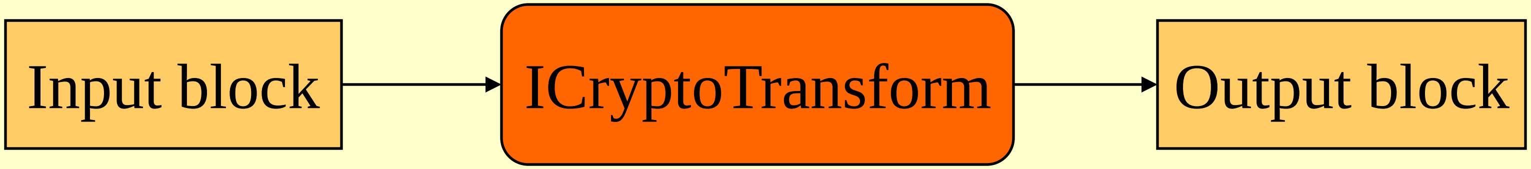
The .NET cryptographic library

- CSP based library that uses inheritance based decoupling
- Bulk data processing algorithms are all made available as ICryptoTransforms
- Essentially 2 methods: TransformBlock() and TransformFinalBlock()



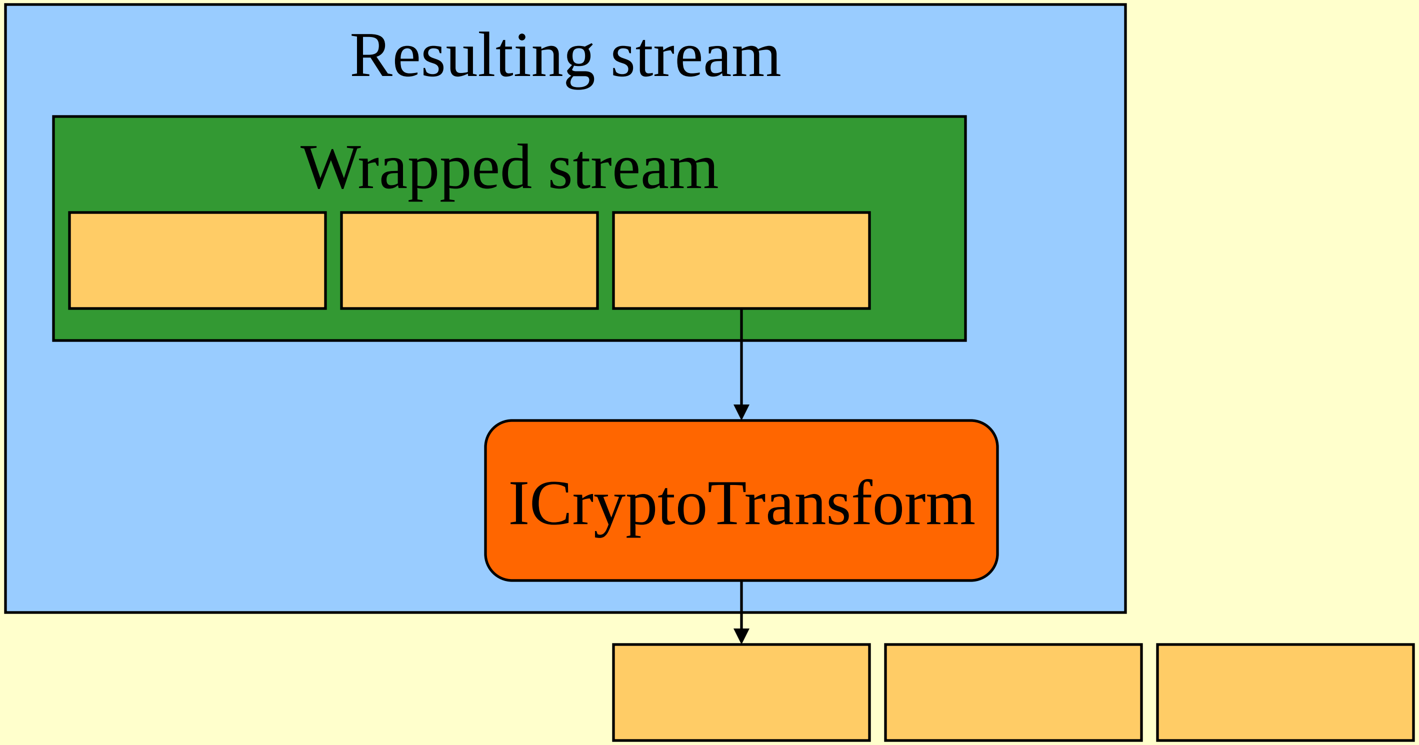
Input block

ICryptoTransform

Output block

ICryptoTransform and CryptoStream

- ICryptoTransforms can wrap streams
  E.g. (in read mode)



Bulk data engine classes

- SymmetricAlgorithm, with algorithm classes
  - TripleDES, DES, Rijndael, …
- HashAlgorithm, with algorithm classes
  - SHA1, MD5, …
- KeyedHashAlgorithm, with algorithm classes
  - HMACSHA1, MACTripleDES, …

Asymmetric engine classes

- Generic AsymmetricAlgorithm engine class
  - RSA and DSA algorithm classes
- Specialized engine classes for typical uses of asymmetric cryptography, that take care of padding and formatting
  - AsymmetricKeyExchangeFormatter
  - AsymmetricSignatureFormatter

Engine classes for key generation

- RandomNumberGenerator
  - For generating secure random numbers
- DeriveBytes
  - For deriving key material from passwords

Other functionality in the .NET cryptographic library

- Facilities for interacting with Windows CryptoAPI
  - To manage CryptoAPI Key containers manually
  - To call extended functionality in CryptoAPI 2.0
- Configuration mechanism
  - The factory methods that create engine classes are driven by a configuration file that can be edited to change default algorithms and implementations
- On top of the .NET crypto API, an implementation of XML Digital Signatures is provided

Conclusion

- Cryptographic mechanisms should be used in such away that they are easy to evolve
  - To deal with implementation errors
  - To deal with algorithms being broken
- By structuring a library around CSP's, this can be achieved
- Java and .NET both offer a CSP based library with similar functionalities

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Key Management Issues

- Generating keys
- Key length
- Storing keys
- Key establishment
- Key renewal
- Key disposal

Generating Keys

- Algorithm security = key secrecy
- Key should be hard or impossible to guess
  - Human password → dictionary attack!
  - Better: hash of entire pass-phrase
  - Machine-generated → use cryptographically secure pseudo-random generator

Key Length

- Trade-off: information value ↔ cracking cost
- Symmetric algorithms
  - $1 000 000 investment in VLSI-implementation

56 bits	64 bits	128 bits
1 hour	10 days	10^{17} years

- Public-key algorithms

Year	*vs. Individual*	*vs. Corporation*	*vs. Government*
2000	1024	1280	1536
2005	1280	1536	2048
2010	1280	1536	2048

Storing Keys

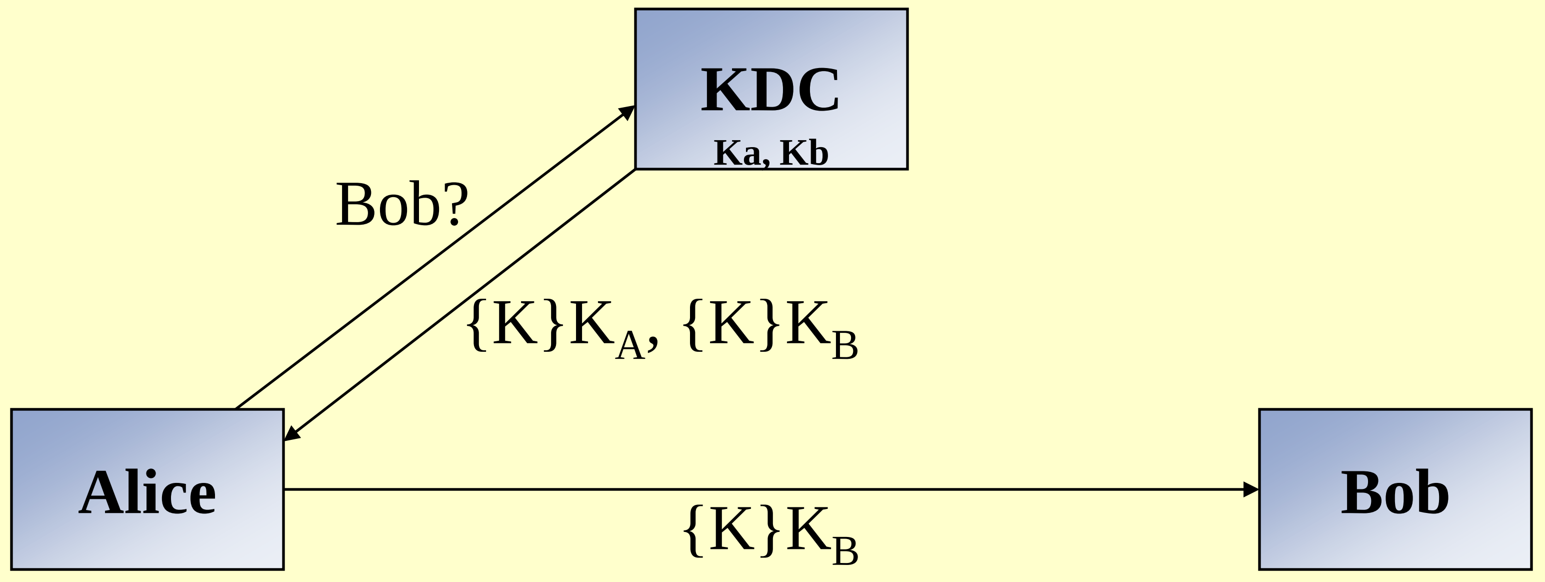
- Simplest: human memory
  - Remember key itself
  - Key generated from pass-phrase
- Use Operating System access control
- Key embedded in chip on smart card
- Storage in encrypted form
  - *Key encryption* keys ↔ *data encryption* keys
- Limit key lifetime depending on
  - Value of the data
  - Amount of encrypted data

Key Establishment

- Key agreement = Two parties compute a secret key together
  - E.g. Diffie – Hellman protocol
- Key distribution or transport = One party generates a key and distributes it in a secure way to all authorized parties

Key Distribution

- Using symmetric encryption
  - Trusted party: Key Distribution Center (KDC)
  - General idea (oversimplified:)



KDC

Ka, Kb

Bob?

$\{K\}K_A, \{K\}K_B$

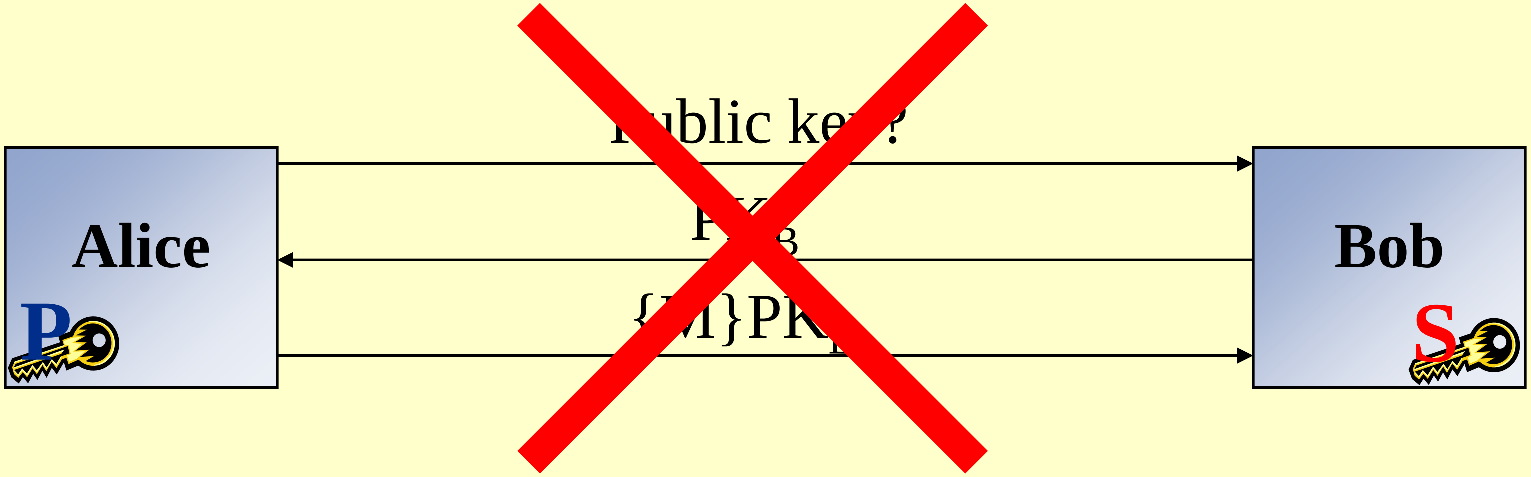
Alice

Bob

$\{K\}K_B$

Key Distribution

- Using public-key encryption
  - No need for KDC?



Alice

P

~~Public key?~~

~~PK_B~~

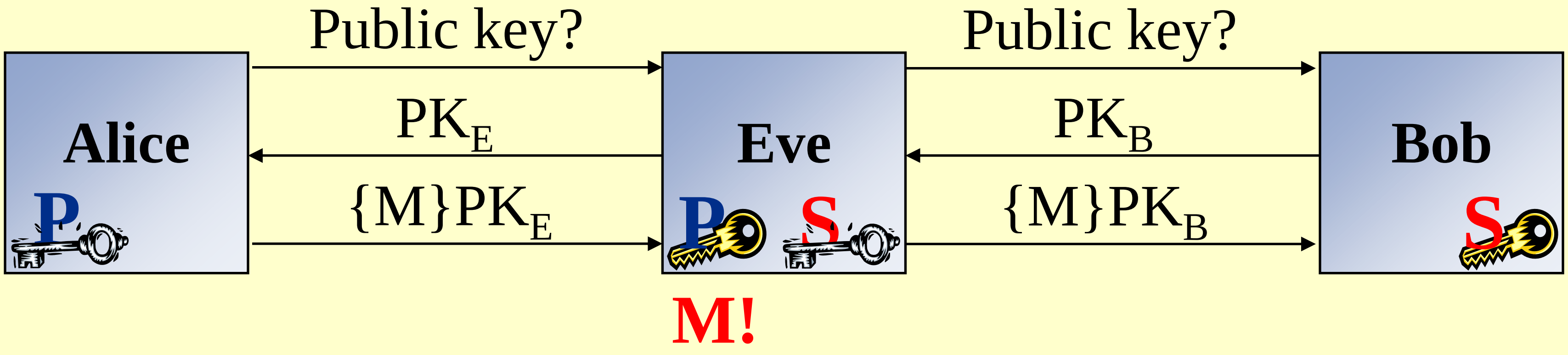
~~$\{M\}PK_B$~~

Bob

S

– Man-in-the-middle attack!

Man-in-the-middle attack



Public key?

Public key?

Alice

Eve

Bob

PK_E

PK_B

$\{M\}PK_E$

$\{M\}PK_B$

P

P **S**

S

M!

- How can Alice be sure she got Bob’s public key?
  - Solution: Certificates

    Public Key Infrastructure (PKI)
  - Discussed later

Key renewal

- Best practice:
  - Limit the amount of data encrypted with a single key
  - Limit the amount of time a key is in use
- Hence:
  - Need for mechanisms to renew keys

Key disposal

- Once a key is no longer used, what should happen?
  - Short-term keys:
    - Dispose in a secure way
  - Long-term keys:
    - Encryption:
      - Reencrypt old data, or store key securely
    - Signing
      - Signing key should be disposed of securely
      - Verification key should be stored securely

Conclusion

- Good key management is essential to achieve any security from cryptography
- Inappropriate
  - Key generation
  - Key storage
  - Or key establishment

is often the cause of security breaches

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Conclusion

- Cryptographic primitives offer well-defined but complex security guarantees
  - Precisely saying what security a crypto primitive offers is non-trivial
- As a consequence, cryptographic primitives are hard to use correctly
  - Mainstream developers should typically **not** use them
  - Use API to higher-level protocols instead