Introduction to Computer Security

What is Computer Security? (1 of 3)

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It is the “Art & Science” of protecting or securing computer systems

What is Computer Security? (2 of 3)

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It is the "Art & Science" of protecting/securing computer systems

- What does protecting or securing mean?
  - Examples:
    - protecting your computer against viruses or other malware
    - protecting your information (e.g., tax returns) from being taken or accessed by others (*unauthorized)*

What is Computer Security? (3 of 3)

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It is the "Art & Science" of protecting/securing computer systems?

- Why is it considered both "Art and Science"
  - while many things in computer security are science or engineering, some aspects remain an 'Art'
  - Examples: security mindset, designing ciphers, etc

Why do we need computer security? (1 of 2)

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Because we need to protect or secure computers against …. adversaries

Why do we need computer security? (2 of 2)

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Because we need to protect or secure computers against …. adversaries

- Who are these *adversaries?*
  - Prying family/friends (?) ☺
  - Mischief makers (script kiddies)
  - Hackers (fame/money/…)
  - Hacktivists (hackers but motivated by a cause)
  - Organized crime
  - Nation states
  - …

Why is computer security challenging?

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- Both systems to be protected and security mechanisms can be quite complex and subtle
- Security mechanisms themselves might become targets or introduce unintended weaknesses
- A single weakness can bring down the system – defenders have to work harder
- Systems, environments, and adversaries are constantly evolving/changing
- Security often tends to be an afterthought rather than designed in
- Users play a crucial role and usable security is hard
- ….

Summary

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- Computer security is the art and science of protecting computer systems against potential adversaries

- Computer security is challenging because of ever changing systems, environments and adversaries, and complexity of systems among other things.

Key Security Notions/Attributes

Confidentiality

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- Preventing unauthorized access or disclosure of data/information
  - Keeping data (and metadata) confidential to authorized parties

- Example:
  - if corporate spies or outsiders gain access to coca-cola's formula that would be a serious loss of confidentiality

Privacy

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- Preventing unauthorized access or disclosure of information/data **about people**

- An individual's right to decide who gets access to information/data about them

- Examples:
  - if attackers breach Target to steal credit card numbers from Target or breach IRS to steal SSN that would be a violation of privacy
  - if a hospital shares your medical information with others without your permission that would be a breach of privacy

Integrity

- Preventing against unauthorized modifications
  - Data Integrity (integrity)
  - Origin Integrity (authentication)
  - System Integrity

- Examples:
  - overwriting your bank balance file/database
  - forged from address in e-mail, junk call, IP packet
  - malware on computer (unauthorized change to system)

Availability

- Ensuring timely availability of (data, system service etc.)

- Example:
  - Denial-of-service attack taking down a network/server

Authenticity

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- Property of being genuine; can be verified and trusted
  - How is this related to integrity?
- Example:
  - A pirated copy of software

Accountability

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- Requirement for entity actions to be traced uniquely to that entity
- Non-repudiation
  - one cannot repudiate one's actions
- Example:
  - paying with a credit card and later claiming never having done the transaction

Summary

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- Key Security Attributes:
  - Confidentiality
  - Integrity
  - Availability
  - Privacy
  - Authenticity
  - Accountability
- Confidentiality, Integrity and Availability are remembered as ‘CIA’
- These notions are not all independent
  - Confidentiality or Secrecy <-> Privacy
  - Integrity <-> Authenticity

Some Computer Security Terminology

Asset

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- Something of value

- Examples:
  - data, system, service, networks, hardware, compute cycles etc.

Threat

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- Set of circumstances that has the potential to breach security and cause harm
- Example:
  - exposure of customer data
  - corruption of database

Some common threats

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- Snooping or interception
  - Unauthorized interception of information
- Falsification
  - Unauthorized change of information
- Masquerading or spoofing
  - An impersonation of one entity by another
- Repudiation
  - A false denial of receiving some information or taking an action.

Are all threats/attacks equally important?

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- Low Impact
  - Limited adverse impact – e.g., loss of time/productivity
- Moderate Impact
  - Serious adverse impact – e.g., some loss of revenue, loss of capability
- High Impact
  - Severe or catastrophic – e.g., potentially bankrupting, loss of life or physical harm

Adversary

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- Threat agent or an entity that materializes the threat

- Examples:
  - a hackers group that is targeting your customer data

Vulnerability

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- A weakness in the system that could potentially be exploited to violate security property of interest

- Examples:
  - A misconfiguration or weak security configuration in a computer
  - A bug in the software that could be exploited; like Heartbleed in OpenSSL
  - Weak passwords

Attack

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- When an entity exploits a vulnerability in a system to violate a security property/attribute

- Examples:
  - an attacker exploits heartbleed bug to steal your cryptographic keys
  - an attacker guesses your weak password to take over your account

Control or Countermeasure

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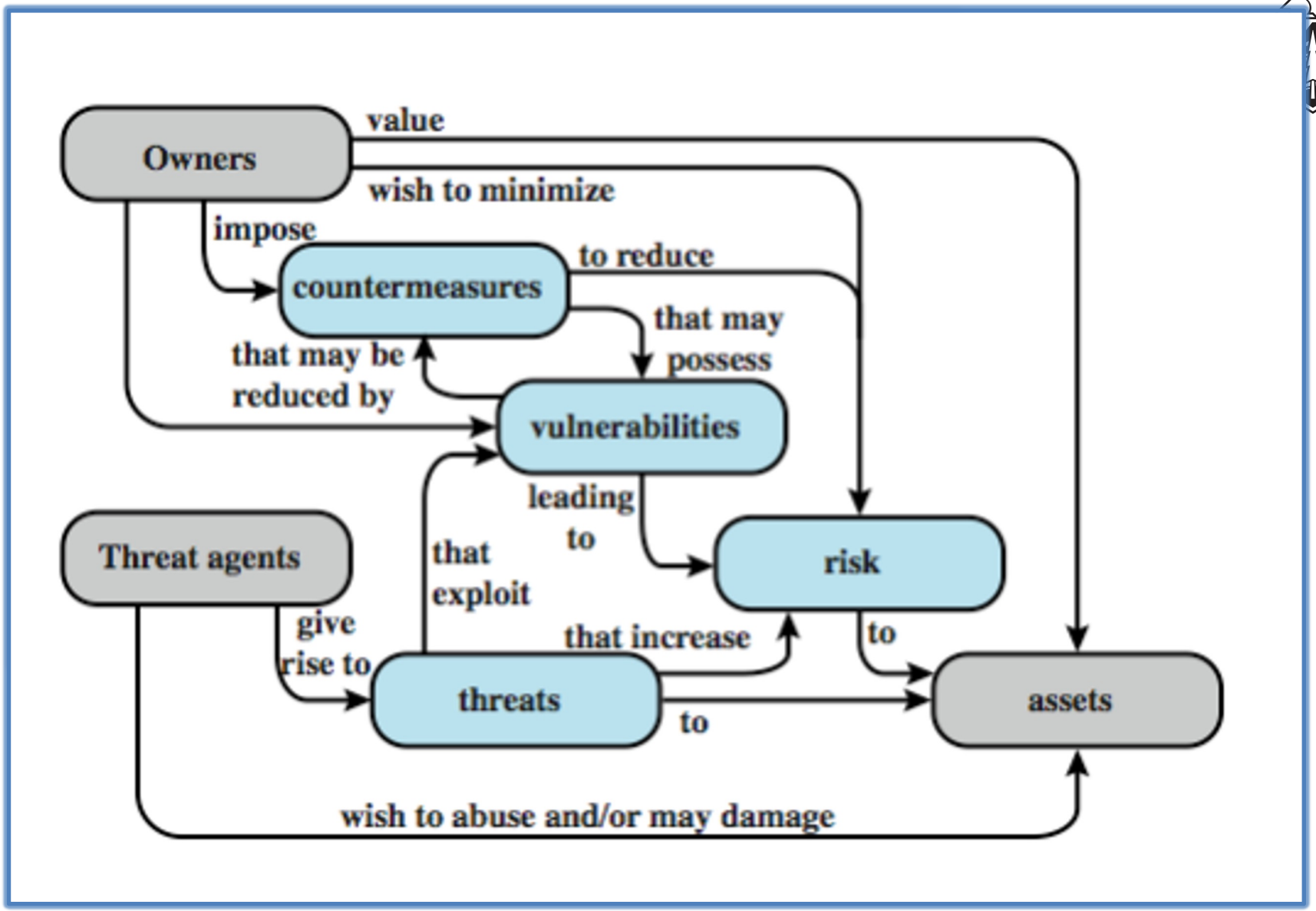
- A means or method to
  - prevent a vulnerability from being exploited;
  - or minimize harm from the vulnerability/attack;
  - or detect attack so response and recovery actions may be initiated
  - or respond to or recover from an attack

- Examples:
  - Storing sensitive data encrypted to mitigate the impact of data being stolen
  - An independent data back-up system to prevent loss of data from failures and ransomware attacks



Stallings & Brown

Attack Surface

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- Is it the sum of vulnerabilities?
- Is it the sum of all exploitable vulnerabilities?
- Reachable exploitable vulnerabilities
  - Network
  - Software
  - Human

Attack Surface Categories

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Network

- Vulnerabilities accessible over the network
- Include network protocol vulnerabilities

Software

- Vulnerabilities in application, utility, or operating system code
- Web server software in particular

Human

- Social engineering
- Phishing

Summary

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- We learned the following security terms and relations among them
  - Asset
  - Threat
  - Adversary
  - Vulnerability
  - Controls/Countermeasures
  - Attack Surface

Cyber Security Principles

Security Principles

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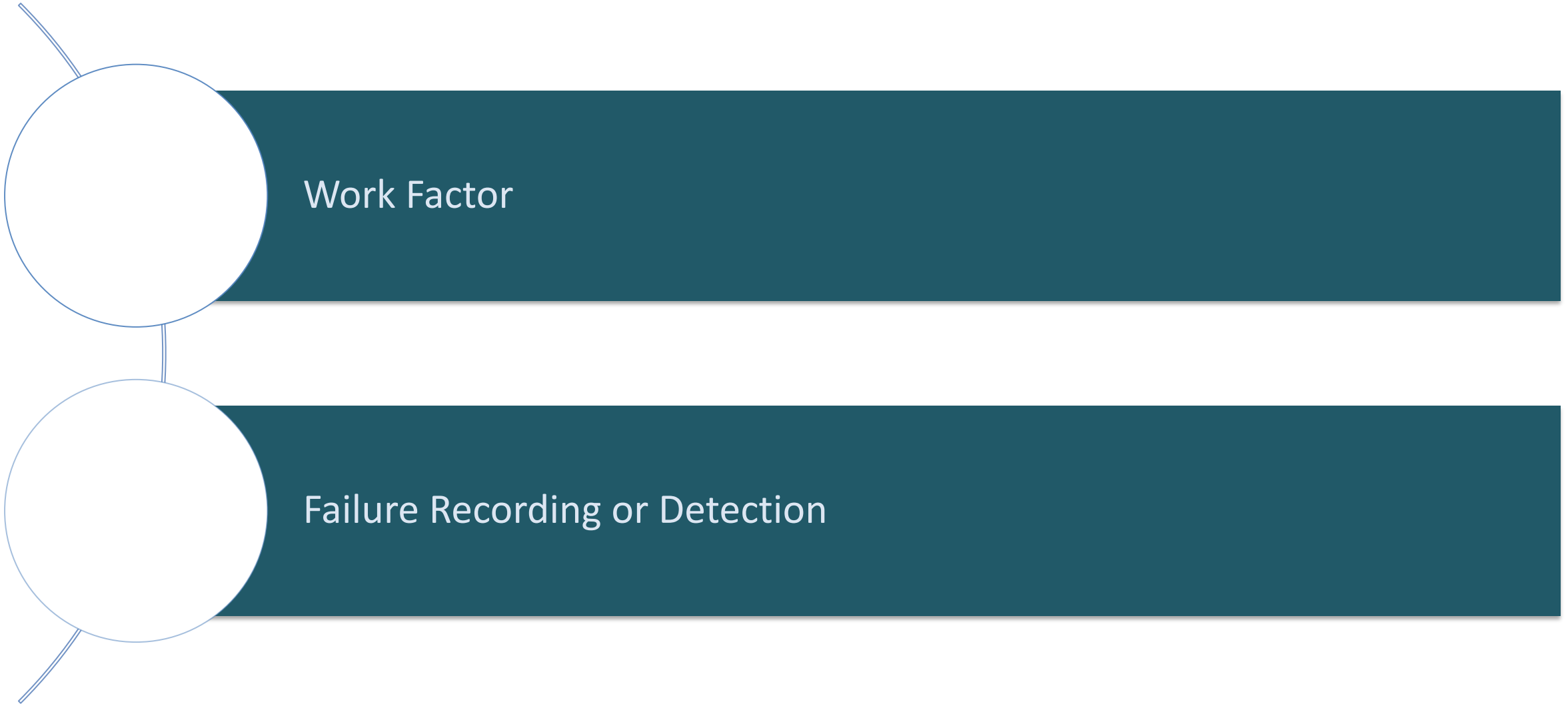
- Economy of Mechanism (Keep it simple)
- Fail-safe (fail-close)
- Complete Mediation
- Open Design
- Separation-of-privilege
- Least-privilege
- Least common mechanism
- Psychological Adoptability (Usability)

Security Principles



Economy of Mechanism

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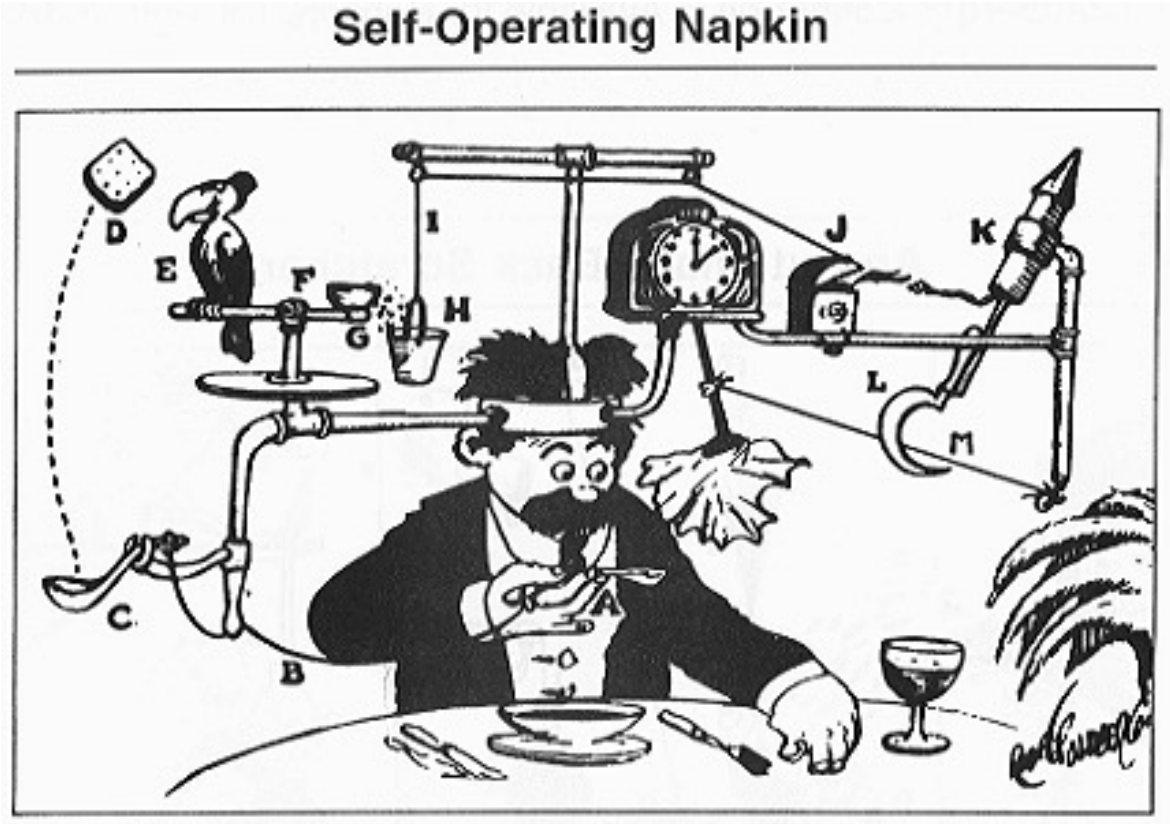
- Keep the design as simple as possible
  - Complex designs will be hard to analyze and verify



Fail-Safe (Fail-Close)

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- Default should be “no-access”
- Access should be based on explicit permissions
- When a system fails it should default to “no-access”

Complete Mediation

- Every access to every object should be checked for authorization
  - Enforces system-wide view of access control
  - Implies we need a fool-proof (secure) way to identify the source of every request
  - Caching access decisions should be avoided or done with care

Open Design

The security of a design should not depend on the design being secret

Rather, design should be open

Security should depend on only specific information such as cryptographic keys, passwords being secret

Separation-of-Privilege

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- Critical operations should be protected using two or more {keys, permissions, passwords} that can then be separated (e.g., 2-man rule)
  - One failure or compromise cannot bring down the system

Least Privilege

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- Every program and every user of the system should operate using the least set of privileges necessary to complete the job
  - Limits the impact/damage of compromise

Least Common Mechanism

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- Minimize the amount of mechanism common to more than one user and depended on by all users
  - shared mechanisms (e.g., shared libraries) may provide information paths from one user to another
  - could be a security risk

Psychologial Adoptability (Usability)

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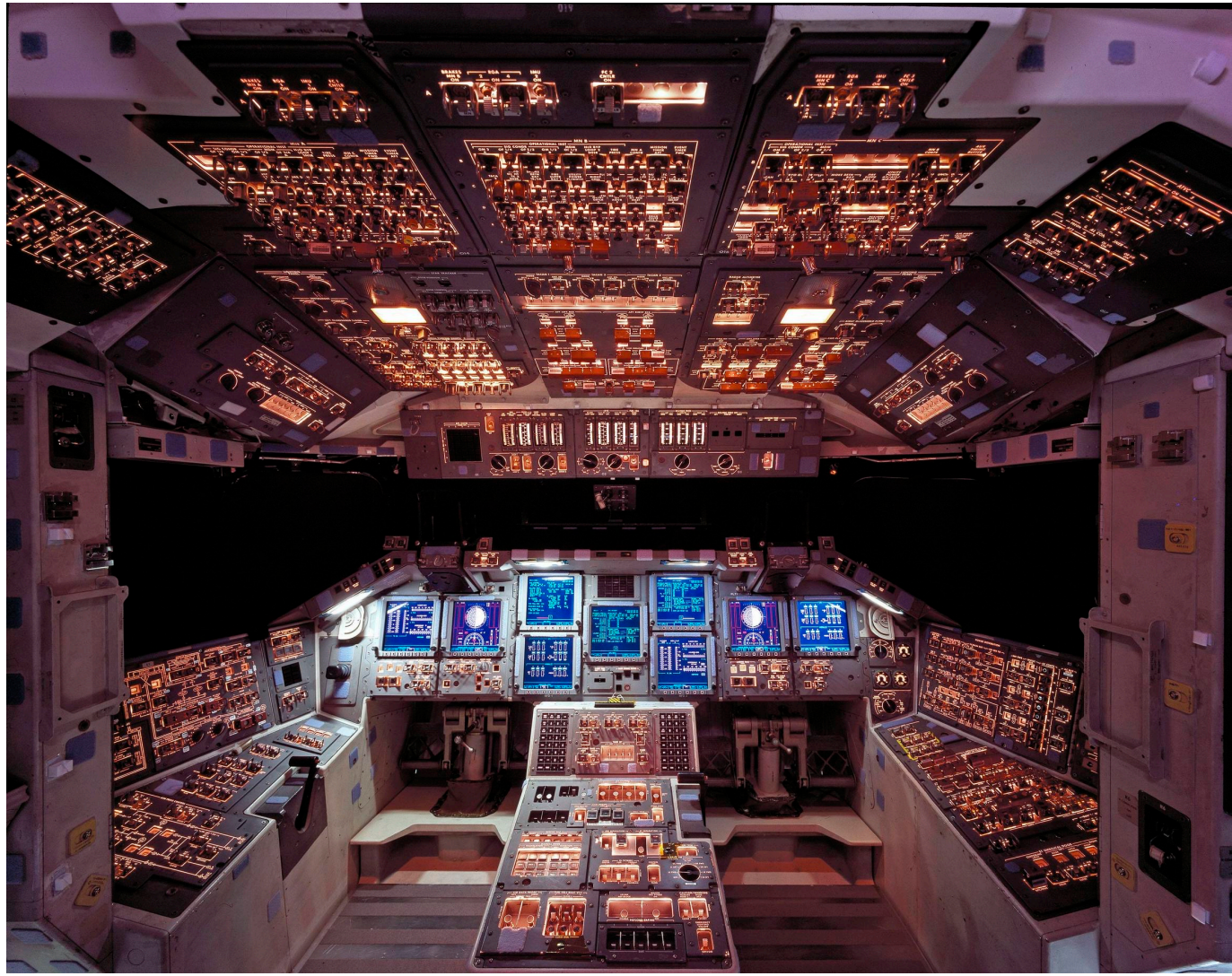
- Essential that human interface be designed for ease of use
  - helps users routinely and automatically apply the protection mechanisms correctly



Work Factor

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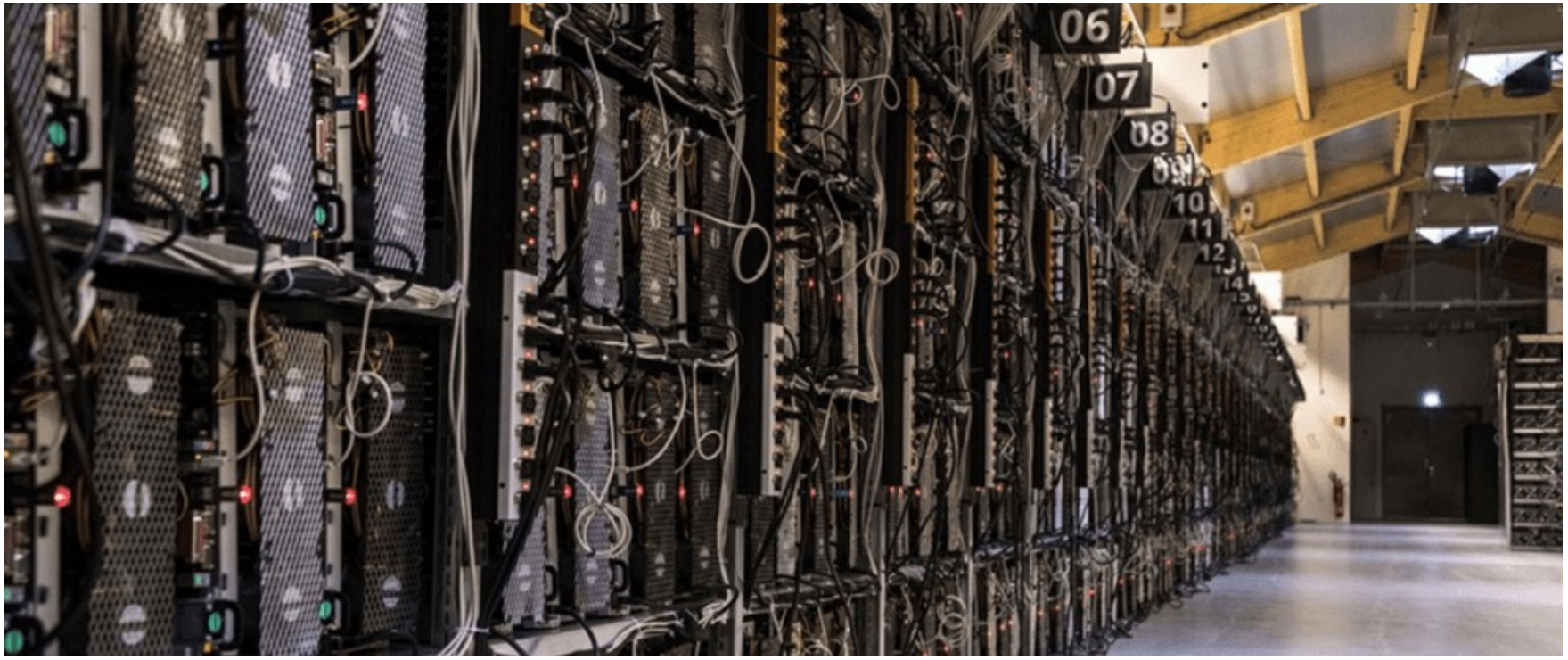
- Compare the cost of circumventing the mechanism with the resources of a potential attacker.



Compromise Recording or Detection

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- mechanisms that reliably record that a compromise of information has occurred can be used in place of more elaborate mechanisms that completely prevent loss
  - argument for detection in place of protection/prevention

Summary

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- Economy of Mechanism (Keep it simple)
- Fail-safe (fail-close)
- Complete Mediation
- Open Design
- Separation-of-privilege
- Least-privilege
- Least common mechanism
- Psychological acceptability (Usability)
- Work Factor
- Failure Recording or Detection

Cyber Security Strategy

Security Strategy

- Specification/Policy
  - What does it mean to be secured in particular?
- Implementation/Mechanism
  - How to enforce the specified security policy?
- Correctness/Assurance
  - Does the security system work as expected/advertised?
- Incentives
  - Are there right incentives for creating right policy, right mechanisms, and using them?

"You must pinky-swear to never reveal our company secrets. That's the cornerstone of our new information security program."

Specification/Policy

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- Policy
  - A statement of what is and what is not allowed
  - Divides the world into secure and non-secure states
  - A secure system starts in a secure state. All transitions (changes in system state) keep it in a secure state
- Specification considerations
  - Security vs. ease of use
  - Return on investment – security business case

Is this situation secure?

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- Web server accepts all connections
  - No authentication required
  - Self-registration
  - Connected to the Internet

Security Mechanism

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A method, tool, or procedure for enforcing a security policy

- Prevention
  - e.g., encrypting data to preserve confidentiality
- Detection
  - e.g., using integrity checks like crypto hashes to detect tampering
- Response
  - e.g., locking out an account that had too many failed login attempts
- Recovery
  - e.g., backing up data to remote secure storage to recover from data loss

Trust and Assumptions

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Locks prevent unwanted physical access

What are the assumptions this statement builds on?

Assurance

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- Evidence of how much to trust a system
- Evidence can include
  - System specifications
  - Design
  - Implementation

Aspirin Assurance Example

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- Why do you trust Aspirin from a major manufacturer?
  - FDA certifies the aspirin recipe
  - Factory follows manufacturing standards
  - Safety seals on bottles
- Analogy to software assurance

Incentives

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- Incentives driving the policy
  - what should be allowed and what shouldn't be and why?
- Incentives driving mechanisms
  - should I use passwords or hardware-tokens?
- Incentives driving usage
  - what incentives are there for me to choose a strong password? for not writing it down?
- Incentives driving attackers
  - money? fame? ease of breaking in? fun?

Summary

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- We examined the four prongs of a good security strategy
  - Security Policy
  - Security Mechanisms
  - Assurance or Correctness
  - Incentives

What is Cryptography

What is Cryptography (1 of 2)

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Literally…

"Secret Writing"

- Historically focused on encryption
  - Ceaser Cipher is one well-known historical example

What is Cryptography (2 of 2)

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- Today: much more than secret writing

- Tools & techniques for securing information
  - at rest
  - in transit
  - and even during computations

- A very important piece of security puzzle
  - albeit not a silver bullet

Some Key Cryptographic Tools (1 of 2)

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- Encryption/Ciphers
  - support Confidentiality and Privacy
  - e.g., AES, 3DES, RSA, ElGamal

- Cryptographic Hashes
  - support Integrity
  - e.g., SHA-256, SHA-512

Some Key Cryptographic Tools (2 of 2)

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- Message Authentication Codes (MACs)
  - support Integrity
  - e.g., HMAC-SHA256, AES-CBC-MAC

- Digital Signatures
  - support Integrity, Authenticity and Non-repudiation
  - e.g., RSA, DSS

Summary

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- Cryptography was historically focused on encryption or ‘secret writing’

- Today provides many essential tools beyond encryption for computer and data security

What is Encryption?

What is Encryption? (1 of 3)

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Encryption primitives or Ciphers are cryptographic primitives used for preserving data confidentiality (and privacy)

What is Encryption? (2 of 3)

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Encryption transforms ‘plaintext’ (comprehensible) data into ‘ciphertext’ (incomprehensible) data

```
HELLO WORLD ----> KHOOR ZRUOG
```

What is Encryption? (3 of 3)

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Knowledge of the ‘cryptographic key’ used for the transformation is needed to reverse the transformation

Types of Encryption

Two main types for encryption

- Symmetric Encryption
  - Key used for enciphering (encryption) and deciphering (decryption) is the same
  - Hence the name symmetric (also called secret-key encryption)
  - Historical (classical) crypto is symmetric

- Asymmetric (or Public-Key) Encryption
  - Keys used for for enciphering (encryption) and deciphering (decryption) are related but different
  - Hence the name asymmetric (also called public-key encryption)
  - Asymmetric crypto is new

Symmetric Encryption

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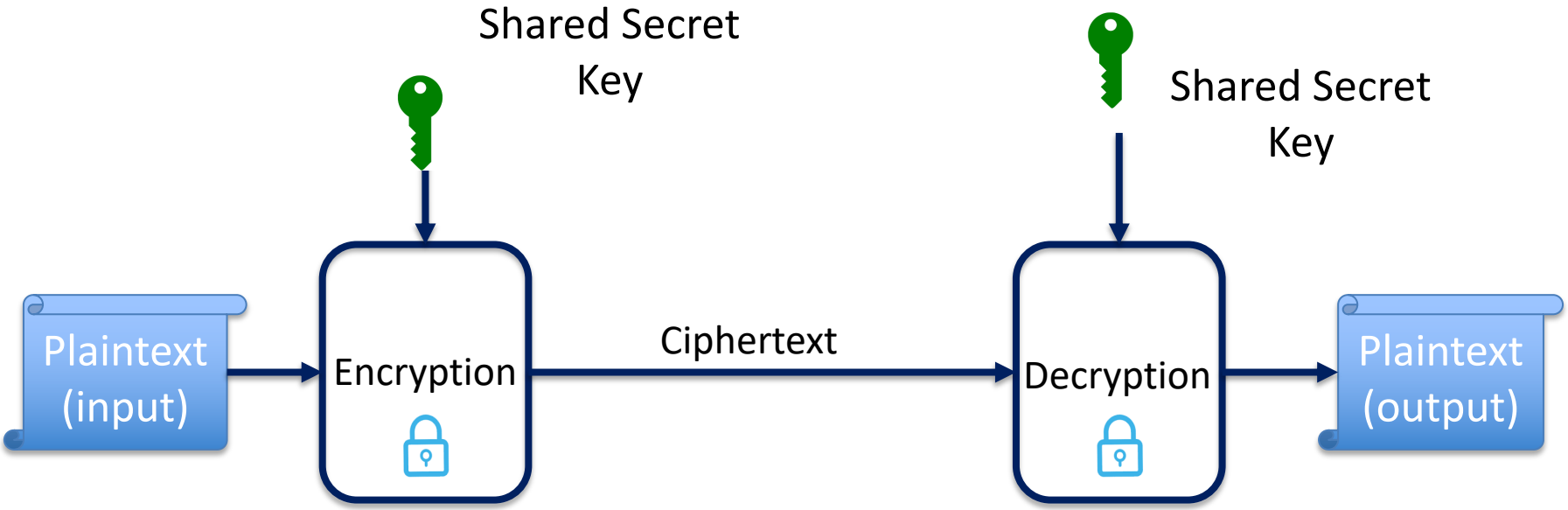
- Widely used; commonly called secret-key encryption
- Provides confidentiality
- Five components
  - Plaintext – original message
    - denoted by m
  - encryption algorithm
    - denoted by E
  - Shared secret key
    - denoted by K
  - ciphertext – encrypted message
    - denoted by c; c = E(m,k) or $E_K(M)$ or c = $\{m\}_K$
  - decryption algorithm
    - denoted by D;
- Correctness
  - m = D(E(m,K), K)


Shared Secret Key
Shared Secret Key
Plaintext (input)
Encryption
Ciphertext
Decryption
Plaintext (output)

Public Key Cryptography

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- Two keys
  - *Private key* known only to individual
  - *Public key* available to anyone

- Usage:
  - Confidentiality: encipher using public key, decipher using private key
  - Integrity/authentication: encipher using private key, decipher using public one
  - Symmetric Key distribution

Asymmetric Encryption

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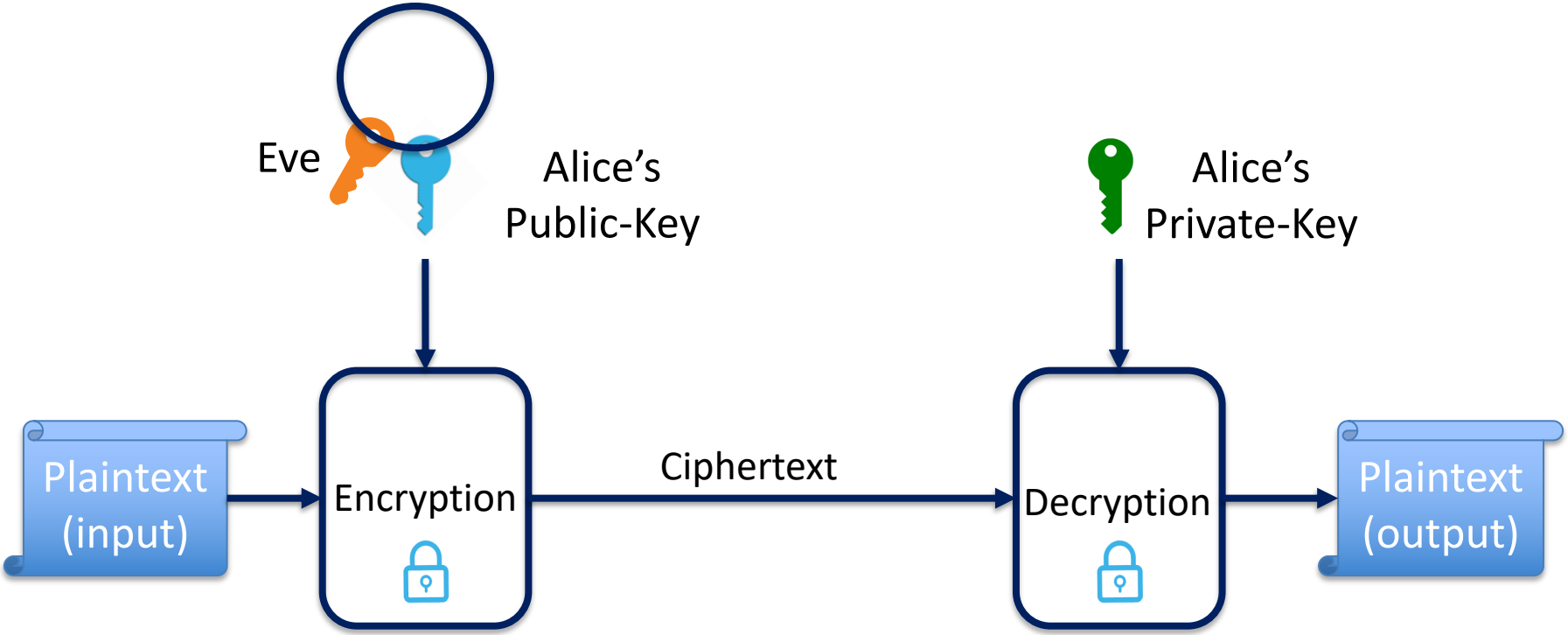
- Widely used; commonly called public-key encryption
- Provides confidentiality
- Five components
  - Plaintext – original message
    - denoted by m
  - encryption algorithm
    - denoted by E
  - key-pair: public-key, secret-key
    - denoted by (PK, SK)
  - ciphertext – encrypted message
    - denoted by c; c = E(m,PK) or $E_{PK}(M)$ or c = $\{m\}_{PK}$
  - decryption algorithm
    - denoted by D;
- Correctness
  - m = D(E(m,PK),SK)


Eve
Alice's
Public-Key
Alice's
Private-Key
Plaintext
(input)
Encryption
Ciphertext
Decryption
Plaintext
(output)

Attacks on Ciphers [1 of 2]

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- Opponent whose goal is to break encryption (cryptosystem) is the *adversary*

- Standard cryptographic practice:
  - Assume adversary knows algorithm used, but not the key
  - **Also Known as : Kerckhoffs's principle** or **Shannon's Maxim**

Attacks on Ciphers [2 of 2]

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Types of attacks

- *ciphertext only*: adversary has only ciphertext; goal is to find plaintext, possibly key
- *known plaintext*: adversary has ciphertext, corresponding plaintext; goal is to find key
- *chosen plaintext*: adversary may supply plaintexts and obtain corresponding ciphertext (access to encryption oracle); goal is to find key
- *chosen ciphertext*: adversary may also supply ciphertexts and obtain corresponding plaintext (access to decryption oracle); goal is to find key

Brute Force Attacks

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- Systematically checking all keys (pass-phrases) with the hope of eventually finding the right key
  - Also known as exhaustive search

- Example:
  - For *ciphertext only*: given a ciphertext try all possible keys to see if a comprehensible plaintext emerges

  - For *known plaintext:* given a ciphertext and plaintext pair try all possible keys to find the key that decrypts the ciphertext to the plaintext

Basis for Attacks

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- Mathematical attacks
  - Based on analysis of underlying mathematics

- Statistical attacks
  - Make assumptions about the distribution of letters, pairs of letters (diagrams), triplets of letters (trigrams), *etc.*
    - Called *models of the language*
  - Examine ciphertext, correlate properties with the assumptions

Summary

- Encryption transforms plaintext (comprehensible) into ciphertext (not comprehensible without the key)
- Two types of Encryption
  - Symmetric: same key for encryption and decryption
  - Asymmetric: different key for encryption and decryption
- Symmetric encryption has been around a long time
  - At least since the time of Caesar
- Asymmetric encryption is newer (publicly known since late 70's)
- Adversaries can try to break an encryption system
  - try to guess the plaintext by looking at the ciphertext
  - or guess the key after looking at one or more (plaintext, ciphertext) pairs

Classical Ciphers

Classical Ciphers [1 of 3]

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- Encryption or ciphers have been around for a long time
  - At least since Caesar's time
  - Caesar Cipher is a well-known historical example

Classical Ciphers [2 of 3]

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- Classical ciphers are ***symmetric***
  - Sender, receiver share common key
  - Keys may be the same, or trivial to derive from one another

- Two basic types
  - *Transposition* ciphers
  - *Substitution* ciphers
  - Combinations are called *product ciphers*

Classical Ciphers [3 of 3]

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- Transposition Ciphers
  - Permute the symbols (characters) in the message
  - Examples: Rail cipher, n-transpositional cipher, scytale
- Substitution Ciphers
  - Substitute the symbols (characters) in the message
  - Examples: Cæsar cipher, One Time Pad, Book cipher

Transposition Cipher [1 of 3]

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- Plaintext and Ciphertext use the same alphabet
- Scramble letters in plaintext to produce ciphertext

- Example (Rail-Fence)
  - Plaintext is `HELLO WORLD`
  - Write the plaintext on alternating "rails"
    - »H E
    - »L L
    - »O W
    - »O R
    - »L D
  - Ciphertext is `HLOOLELWRD`

Transposition Cipher [1 of 2]

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- Generalize to n-columnar transpositions
- Write text in fixed length rows.
- Read ciphertext out in column major order

```
H E L
L O W
O R L
D X X
HLODEORXLWLX
```

  - Could also permute the columns

Transposition Ciphers [1 of 3]

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- What is the key in Rail-Fence or n-columnar transposition?

Other Transposition Ciphers

- Scytale (older than 300BC in Greece!)

Columnar Transposition

- # of columns and order of columns is encoded by a key
  - Ex: “WORD” ⇒ 4 columns and rearranged in the order 4, 2, 3, 1
    - W is 4th alphabetically in the key
    - 0 is 2nd alphabetically in the key...

Double Columnar Transposition

- Apply Columnar Transposition twice
  - Can use two different passwords

Double Columnar Transposition

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- Apply Columnar Transposition twice
  - Can use two different passwords

- Used in WWI US Military

Double Columnar Transposition

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- Apply Columnar Transposition twice
  - Can use two different passwords
- Used by US Military in WW-I
- Ubchi -- a variation used by Germany in WW-I
  - Same password twice
  - different padding

Substitution Ciphers [1 of 2]

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- Change characters in plaintext to produce ciphertext

- Example (Cæsar cipher)
  - Plaintext is `HELLO WORLD`
  - Change each letter to the third letter following it (A goes to D, X goes to A, Y to B, Z to C)
  - Ciphertext is `KHOOR ZRUOG`

Caesar Cipher

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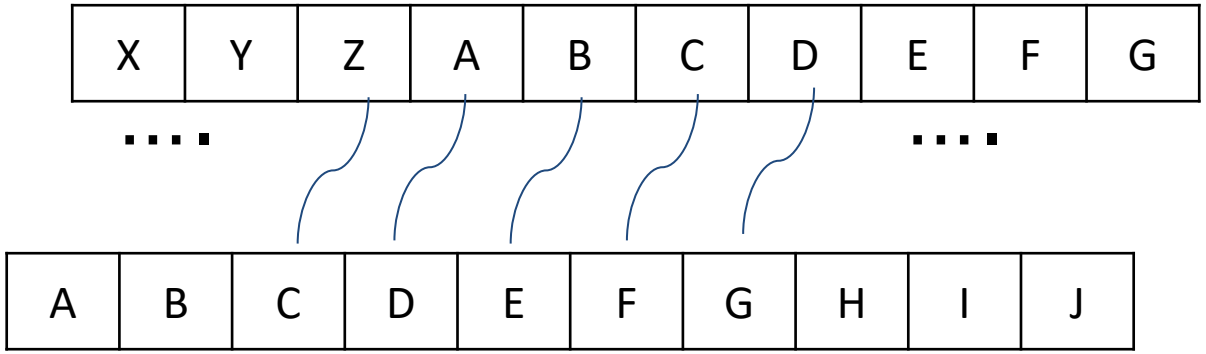
Reportedly used by Julius Caesar

- It is a shift cipher with a shift of 3 (A → D)



Caesar Cipher

Plaintext: Hello World

H → K, E → H, L → O, O → R

⇒ Hello → Khoor

W → Z, O → R, R → U, L → O, D → G

⇒ World → Zruog

Caesar Cipher

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It is a Substitution Cipher:

Plaintext Alphabet:

A	B	C	D	E	F	G	H	I	J	…

Ciphertext Alphabet:

D	E	F	G	H	I	J	K	L	M	…

Keys in Ciphers

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- What is the “key” for Caesar Cipher?

Caesar Cipher Exercise

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http://rumkin.com/tools/cipher/

Decode

Fdhvhu Vkliw Lv Grsh

Other Substitution Ciphers

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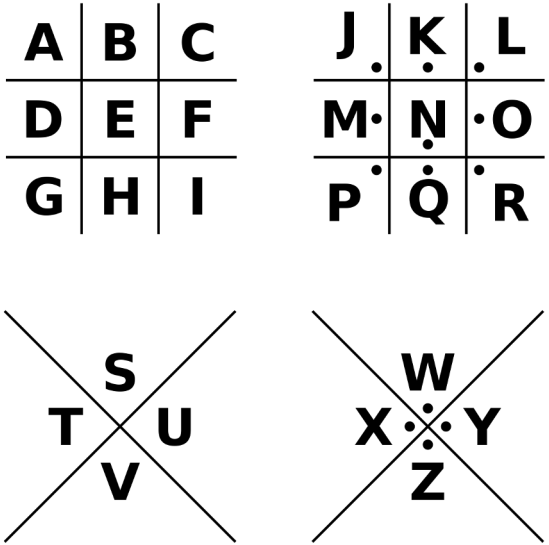
- Pigpen (Masonic or Tic-Tac-Toe) Cipher



Other Substitution Ciphers

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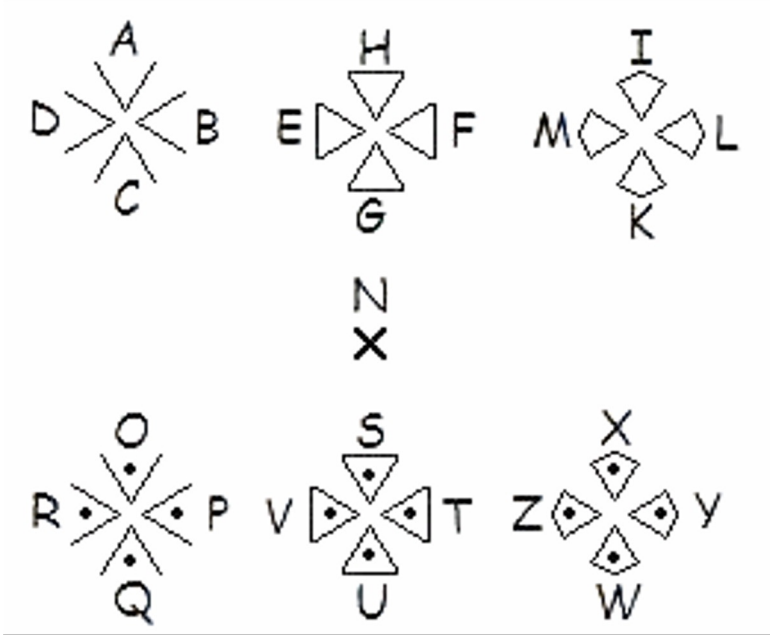
- Templar Cipher



Other Substitution Ciphers

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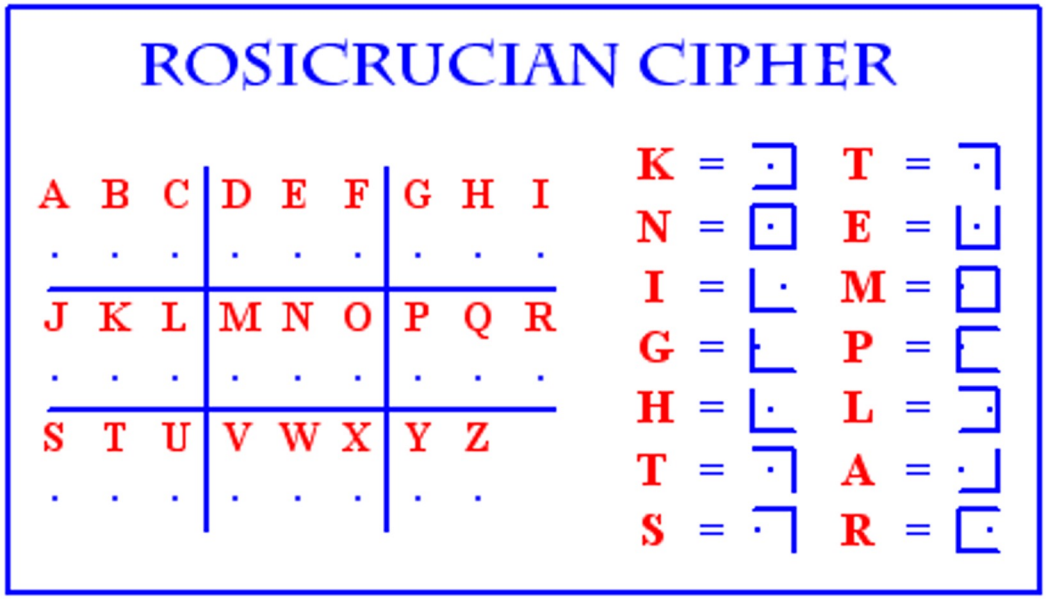
- Rosicrucian Cipher



Keys in Ciphers

- What is the “key” for Tic-Tac-Toe Cipher?

Other Substitution Ciphers

- Caesar Cipher is "*monoalphabetic*"
  - *one* substitution alphabet
- What if we can combine two alphabets?
  - Ex: one substitution alphabet for odd letters and a different alphabet for one for even letters?
- What if we can use more than two!
  - we get "*polyalphabetic*" ciphers

Polyalphabetic Ciphers

Vigenere Cipher

- Key has multiple letters
  - Ex: "*paswd*"
    - Contrast with Caesar (Key is "*d*")

Polyalphabetic Ciphers

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- `Hello World` with key "`paswd`"
  - Try it on Rumkin!

Polyalphabetic Ciphers

Vigenere Cipher

- Key has multiple letters
  - Ex: "*paswd*"
    - Contrast with Caesar (Key is "*d*")

- `Hello World` with key "`paswd`"
  - Try it on Rumkin!
    - `Wedhr Lojhg`

Cryptanalysis

- Both Ceasar and n-columnar are easily breakable!

- Example: breaking Ceasar Cipher
  - Brute Force: try all possible (26) keys
  - Statistical: look at letter frequencies
    - "E" is the most common letter in English language
    - most common letter in ciphertext likely corresponds to "E"

Cryptanalysis - Breaking Ciphers!

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Abu Yusuf Al Kindi, Arab mathematician, philosopher from 9th century AD is credited with discovering *frequency analysis*

One-Time Pad

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- A cipher with a random key at least as long as the message
  - Provably unbreakable!!
  - Why?

- Let us consider a one-time pad scheme that uses Caeser Cipher

One-Time Pad

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- Look at ciphertext `DXQR`.
- Equally likely to correspond to plaintext `DOIT` (key `AJIY`) and to plaintext `DONT` (key `AJDY`) and any other 4 letters

- Warning: keys *must* be random, or you can attack the cipher by trying to regenerate the key
  - Approximations, such as using pseudorandom number generators to generate keys, are *not* random

Book Cipher

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- Approximate one-time pad with book text
  - Sender and receiver agree on text to pull key from
  - Bible, Koran, Phone Book
- Problem is that book text is not random
  - Combine English with English
  - Can still perform language based statistical analysis

Summary

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- Classic ciphers are symmetric
- They are either transposition (or permutation ciphers), substitution ciphers, or product ciphers (combination)
- These pen and paper classical ciphers have been used historically
- Not practical in the age of the computer – easy to break
- The components (transposition and substitution) are the same in modern ciphers
- One-time pad is provably unbreakable!