CMSC414 Computer and Network Security

Intro to Cryptography

Yizheng Chen | University of Maryland
surrealyz.github.io

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Credits: some slides were from Suman Jana and CS161 instructors at UC Berkeley. Blue slides will not be tested.

Announcement

- Project 2 due on Thursday, March 5

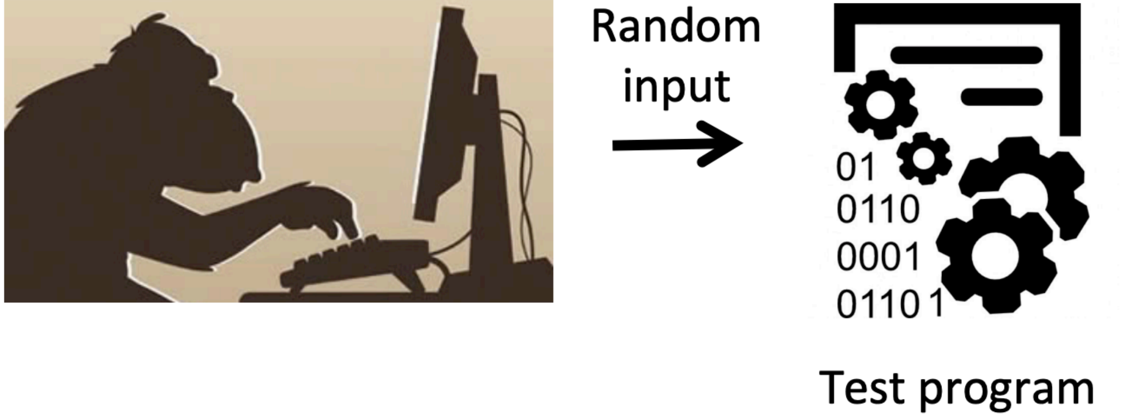
Agenda

- Fuzzing
- Intro to Cryptography

Fuzzing

- **Fuzzing**, or **fuzz testing**, is an automated software testing technique that involves providing invalid, semi-valid, unexpected, or random data as inputs to a computer program.

Blackbox Fuzzing



Random input

Test program

Miller et al. ‘89

Blackbox Fuzzing

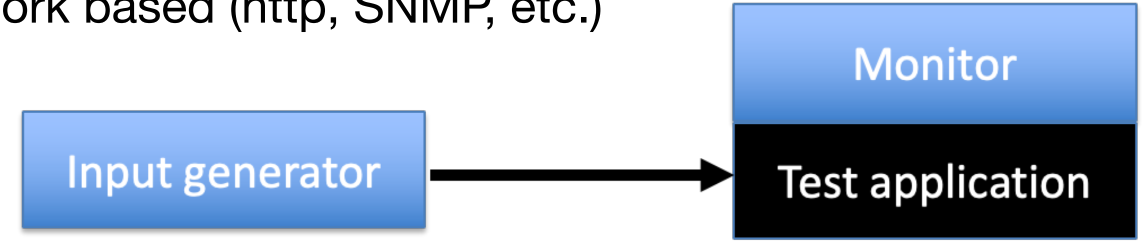
- Given a program, simply feed random inputs and see whether it exhibits incorrect behavior (e.g., crashes)

- Advantage: easy, low programmer cost

- Disadvantage: inefficient
    - Inputs often require structures, random inputs are likely to be malformed
    - Inputs that trigger an incorrect behavior is a very small fraction, probability of getting lucky is very low

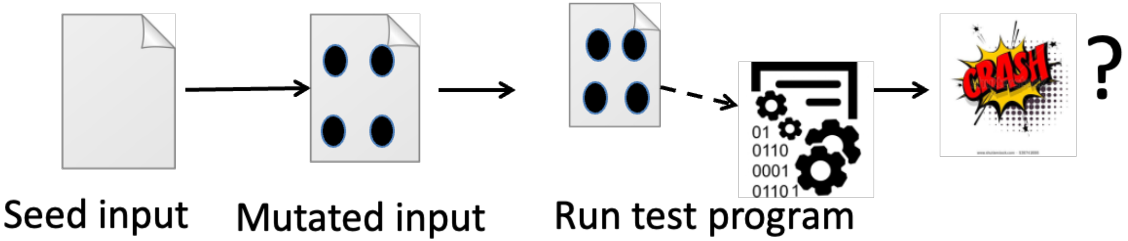
Fuzzing

- Automatically generate test cases
- Many slightly anomalous test cases are input into a target
- Application is monitored for errors
  - See if program crashed, e.g., SEGV vs. assert fail
  - See if program locks up
- Inputs are generally either file based (.pdf, .png, .wav, etc.) or network based (http, SNMP, etc.)



Enhancement 1: Mutation-Based fuzzing

- Take a well-formed input, randomly perturb (flipping bit, etc.)
- Little or no knowledge of the structure of the inputs is assumed
- Anomalies are added to existing valid inputs
  - Anomalies may be completely random or follow some heuristics (e.g., remove NULL, shift character forward)
- Examples: ZZUF, Taof, GPF, ProxyFuzz, FileFuzz, Filep, etc.



Example: fuzzing a PDF viewer

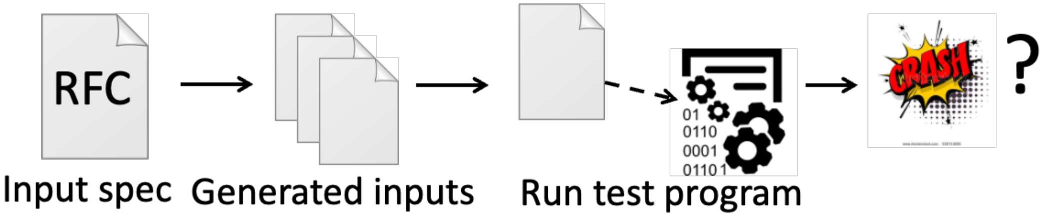
- Google for .pdf (about 1 billion results)
- Crawl pages to build a corpus
- Use fuzzing tool (or script)
    - Collect seed PDF files
    - Mutate that file
    - Feed it to the program
    - Record if it crashed (and input that crashed it)

Mutation-based fuzzing

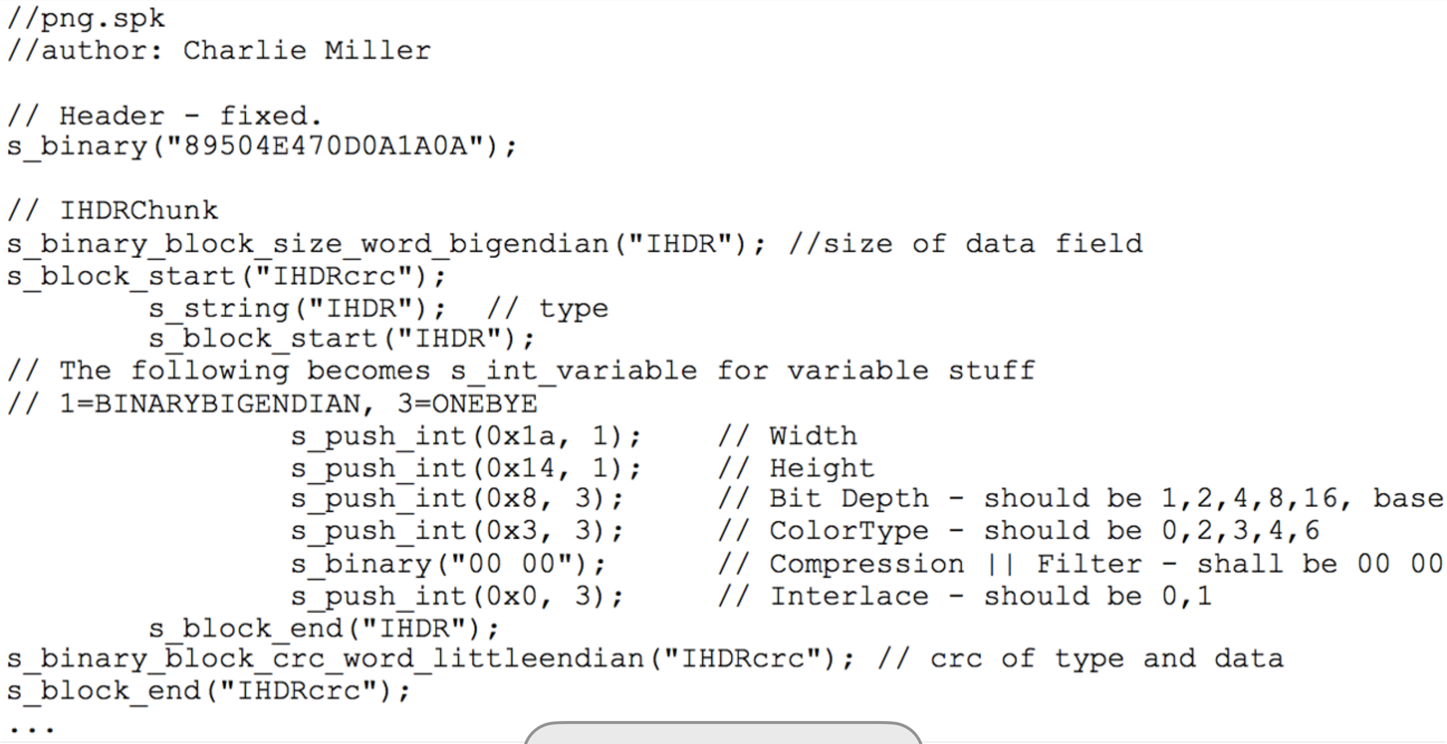
- Advantages:
  - Super easy to setup and automate
  - Little or no file format knowledge is required
- Disadvantages:
  - Limited by initial corpus
  - May fail for protocols with checksums, those which depend on challenge

Enhancement II: Generation-Based Fuzzing

- Test cases are generated from some description of the input format: RFC, documentation, etc.
    - Using specified protocols/file format info
- Anomalies are added to each possible spot in the inputs
- Knowledge of protocol should give better results than random fuzzing



Example: fuzzing a PNG file parser



```
//png.spk
//author: Charlie Miller

// Header - fixed.
s_binary("89504E470D0A1A0A");

// IHDRChunk
s_binary_block_size_word_bigendian("IHDR"); //size of data field
s_block_start("IHDRcrc");
        s_string("IHDR");  // type
        s_block_start("IHDR");
// The following becomes s_int_variable for variable stuff
// 1=BINARYBIGENDIAN, 3=ONEBYE
                s_push_int(0x1a, 1);    // Width
                s_push_int(0x14, 1);    // Height
                s_push_int(0x8, 3);     // Bit Depth - should be 1,2,4,8,16, base
                s_push_int(0x3, 3);     // ColorType - should be 0,2,3,4,6
                s_binary("00 00");      // Compression || Filter - shall be 00 00
                s_push_int(0x0, 3);     // Interlace - should be 0,1
        s_block_end("IHDR");
s_binary_block_crc_word_littleendian("IHDRcrc"); // crc of type and data
s_block_end("IHDRcrc");
...
```

Sample PNG Spec

Mutation-based vs. Generation-based

- Mutation-based fuzzer
  - Pros: Easy to set up and automate, little to no knowledge of input format required
  - Cons: Limited by initial corpus, may fail for protocols with checksums and other hard checks
- Generation-based fuzzers
  - Pros: Completeness, can deal with complex dependencies (e.g, checksum)
  - Cons: writing generators is hard, performance depends on the quality of the spec

How much fuzzing is enough?

- Mutation-based-fuzzers may generate an infinite number of test cases. When has the fuzzer run long enough?

- Generation-based fuzzers may generate a finite number of test cases. What happens when they’re all run and no bugs are found?

Code coverage

- Some of the answers to these questions lie in code coverage
- Code coverage is a metric that can be used to determine how much code has been executed.
- Data can be obtained using a variety of profiling tools. e.g. gcov, lcov

Different Coverage Metrics

- **Line/block coverage:** Measures how many lines of source code have been executed
- **Branch coverage:** Measures how many branches in code have been taken (conditional jmps)
- **Path coverage:** Measures how many paths have been taken

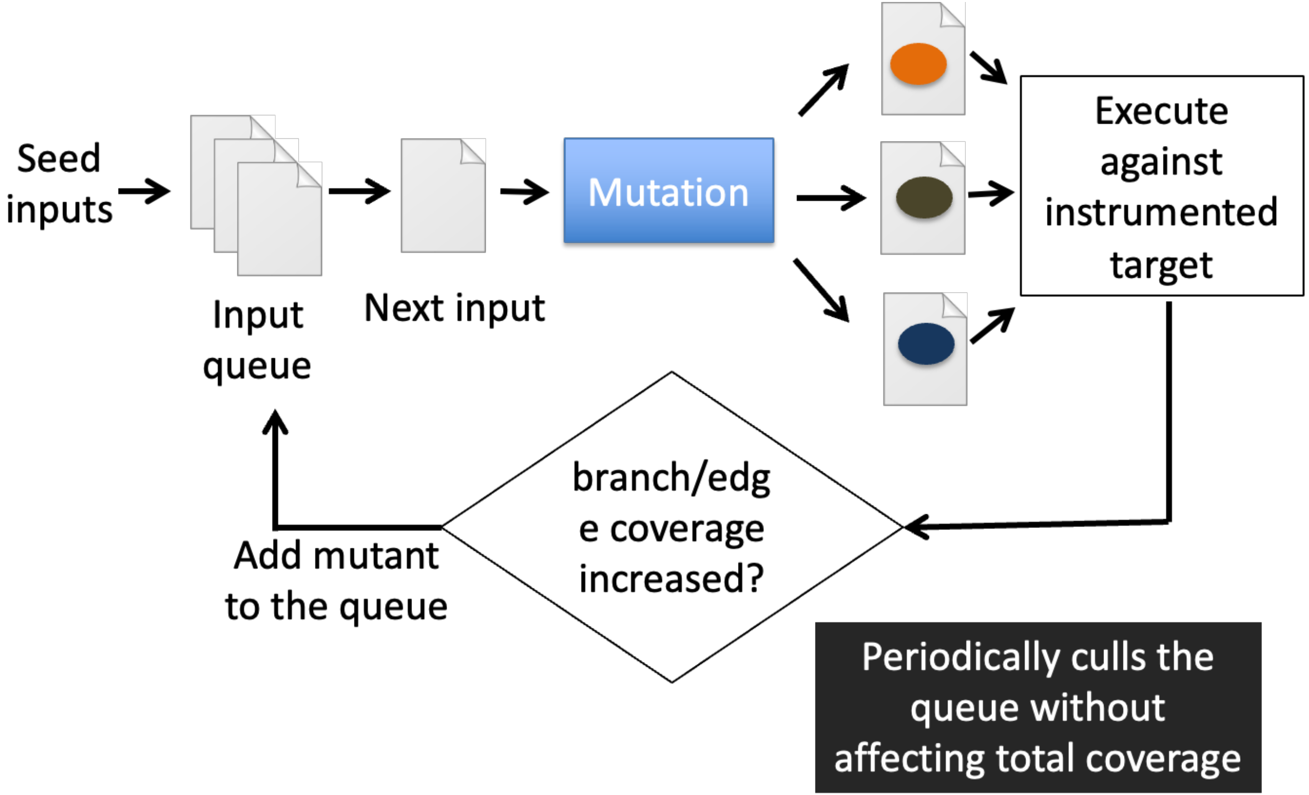
Code coverage

- Pros:
    - Can evaluate an input
    - Can compare fuzzers
    - Am I getting stuck somewhere?
- Cons:
    - Full coverage (any metric) does not guarantee finding the bug

Enhancement III:
Coverage-guided gray-box fuzzing

- Special type of mutation-based fuzzing
    - Run mutated inputs on instrumented program and measure code coverage
    - Search for mutants that result in coverage increase
    - Often use genetic evolution algorithms, i.e., try random mutations on test corpus and only add mutants to the corpus if coverage increases
    - Examples: AFL, libfuzzer

American Fuzzy Lop (AFL)


Seed inputs
Input queue
Next input
Mutation
Execute against instrumented target
branch/edg e coverage increased?
Add mutant to the queue
Periodically culls the queue without affecting total coverage

Agenda

- Fuzzing
- Intro to Cryptography

What is cryptography?

- Older definition: The study of secure communication over insecure channels

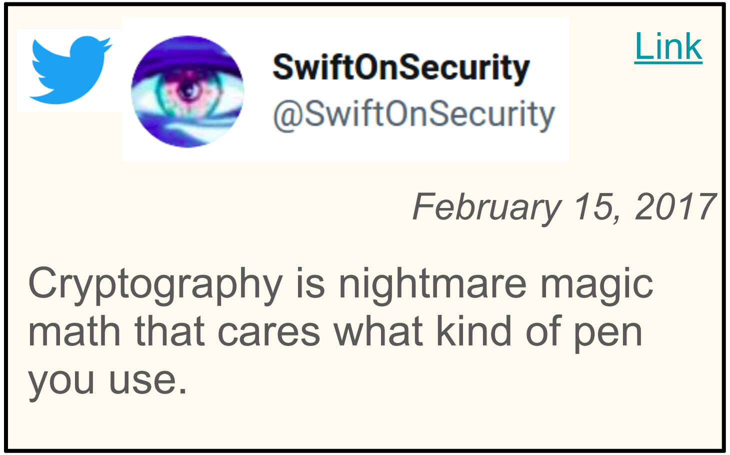
- Newer definition: Provide rigorous guarantees about the data and computation in the presence of an attacker
  - Not just *confidentiality* but also *integrity* and *authenticity*

Don’t try this at home!

- We will teach you the basic building blocks of cryptography, but you should never try to write your own cryptographic algorithms

- It’s very easy to make a mistake that makes your code insecure

- Instead, use existing well-vetted cryptographic libraries
  - This portion of the class is as much about making you a good *consumer* of cryptography



SwiftOnSecurity
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Link

February 15, 2017

Cryptography is nightmare magic math that cares what kind of pen you use.

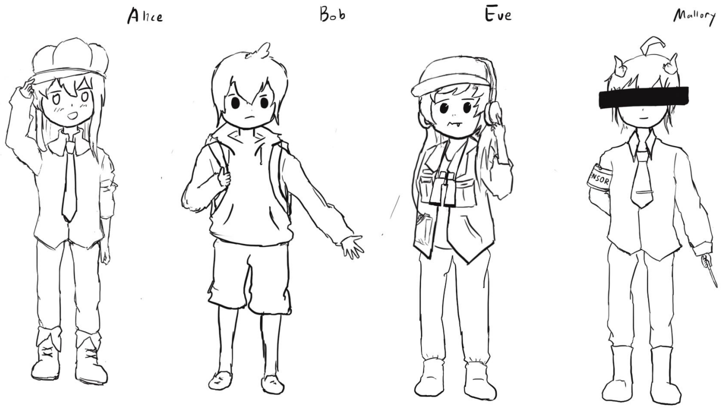
Definitions

Meet Alice, Bob, Eve, and Mallory

- Alice and Bob: The main characters trying to send messages to each other over an insecure communication channel

- Eve: An **eavesdropper** who can read any data sent over the channel

- Mallory: A **manipulator** who can read and modify any data sent over the channel



Meet Alice, Bob, Eve, and Mallory

- We often describe cryptographic problems using a common cast of characters

- One scenario:
  - Alice wants to send a message to Bob.
  - However, Eve is going to *eavesdrop* on the communication channel.
  - How does Alice send the message to Bob without Eve learning about the message?

- Another scenario:
  - Bob wants to send a message to Alice.
  - However, Mallory is going to *tamper* with the communication channel.
  - How does Bob send the message to Alice without Mallory changing the message?

Three Main Goals of Cryptography

- In cryptography, there are three common properties that we want on our data

- **Confidentiality**: An adversary cannot *read* our messages.

- **Integrity**: An adversary cannot *change* our messages without being detected.

- **Authenticity**: I can prove that this message came from the person who claims to have written it.

Three Main Goals of Cryptography

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- **Authenticity**: I can prove that this message came from the person who claims to have written it.
    - Integrity and authenticity are closely related properties…
        - Before I can prove that a message came from a certain person, I have to prove that the message wasn't changed!
    - … but they're not identical properties
        - Later we'll see some edge cases

Keys

- The most basic building block of any cryptographic scheme: The **key**

- Properly chosen and guarded keys “power” the security of our cryptographic algorithms

- Two models of keys:
  - **Symmetric key model**: Alice and Bob both know the value of the same secret key.
  - **Asymmetric key model**: A user has two keys, a secret key and a public key.
    - Example: RSA encryption

Security Principle: Kerckhoff's Principle

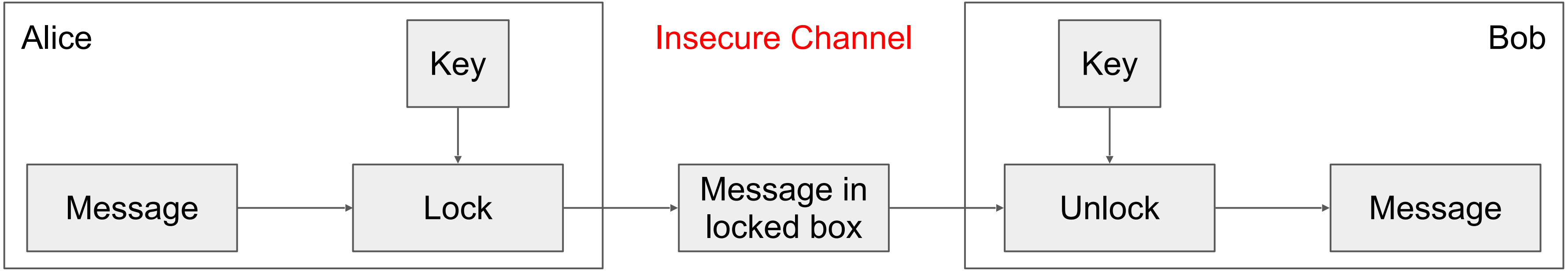
- This principle is closely related to Shannon's Maxim
    - Don't use security through obscurity. Assume the attacker knows the system.

- Kerckhoff's principle says:
    - Cryptosystems should remain secure even when the attacker knows all internal details of the system
    - The key should be the only thing that must be kept secret
    - The system should be designed to make it easy to change keys that are leaked (or suspected to be leaked)

- Our assumption: **The attacker knows all the algorithms we use. The only information the attacker is missing is the secret key(s).**

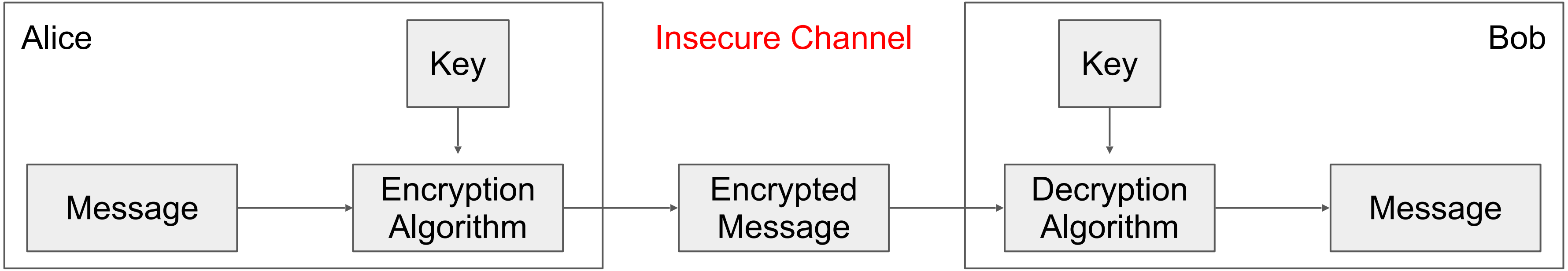
Confidentiality

- **Confidentiality**: An adversary cannot *read* our messages.
- Analogy: Locking and unlocking the message



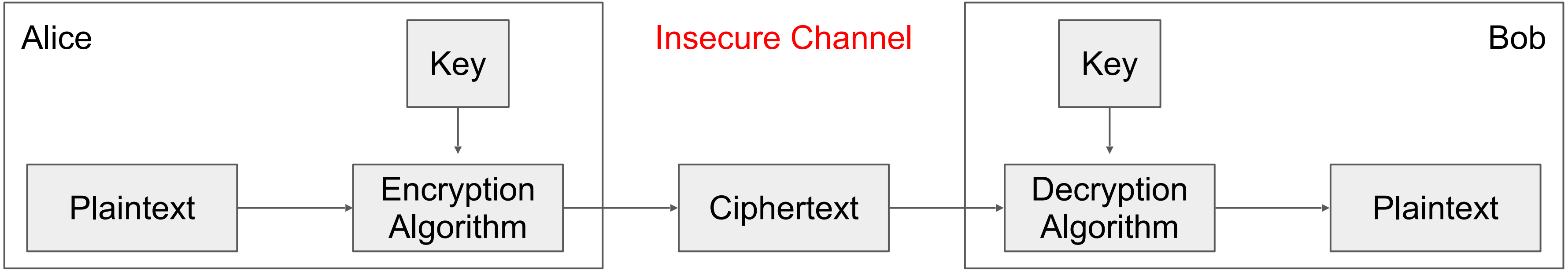
Confidentiality

- Schemes provide confidentiality by **encrypting** messages



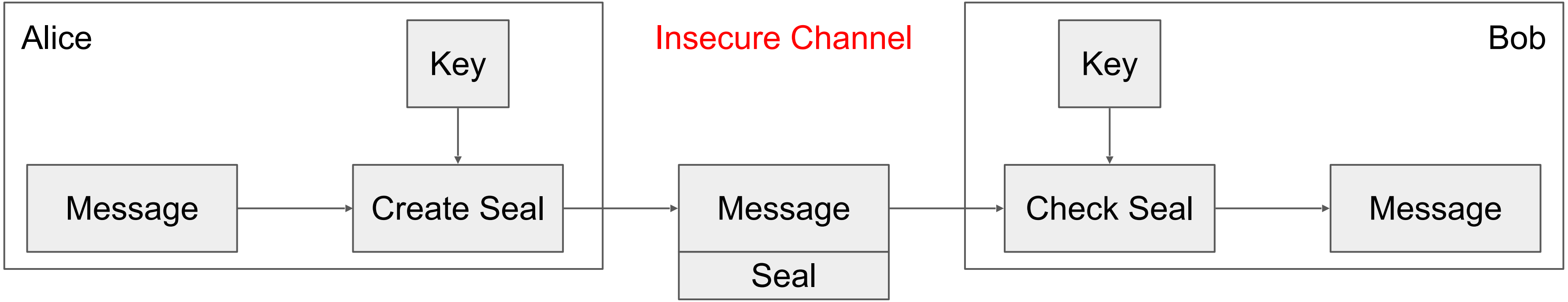
Confidentiality

- **Plaintext**: The original message
- **Ciphertext**: The encrypted message



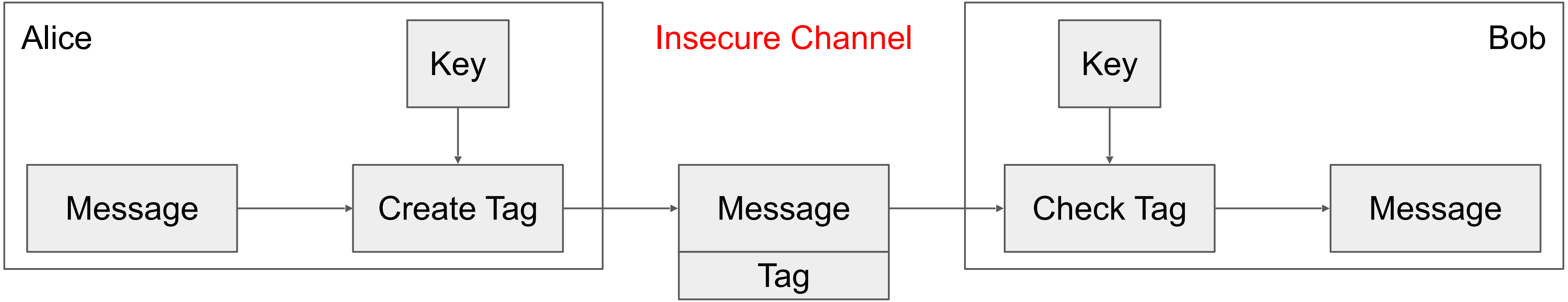
Integrity (and Authenticity)

- **Integrity**: An adversary cannot *change* our messages without being detected.
- Analogy: Adding a seal on the message



Integrity (and Authenticity)

- Schemes provide integrity by adding a **tag** or **signature** on messages
- More on integrity in a future lecture



Threat Models

- What if Eve can do more than eavesdrop?
- Some threat models for analyzing confidentiality:

	Can Eve trick Alice into encrypting messages of Eve's choosing?	Can Eve trick Bob into decrypting messages of Eve's choosing?
Ciphertext-only	No	No
Chosen-plaintext	Yes	No
Chosen-ciphertext	No	Yes
Chosen plaintext-ciphertext	Yes	Yes

Threat Models

- In this class, we'll explain the chosen plaintext attack model
- In practice, cryptographers use the chosen plaintext-ciphertext model
    - It's the most powerful
    - It can actually be defended against

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Cryptography Roadmap

	Symmetric-key	**Asymmetric-key**
Confidentiality	● One-time pads ● Block ciphers with chaining modes (e.g. AES-CBC) ● Stream ciphers	● RSA encryption ● ElGamal encryption
Integrity, Authentication	● MACs (e.g. HMAC)	● Digital signatures (e.g. RSA signatures)

- Hash functions
- Pseudorandom number generators
- Public key exchange (e.g. Diffie-Hellman)

- Key management (certificates)
- Password management

Symmetric-Key Encryption

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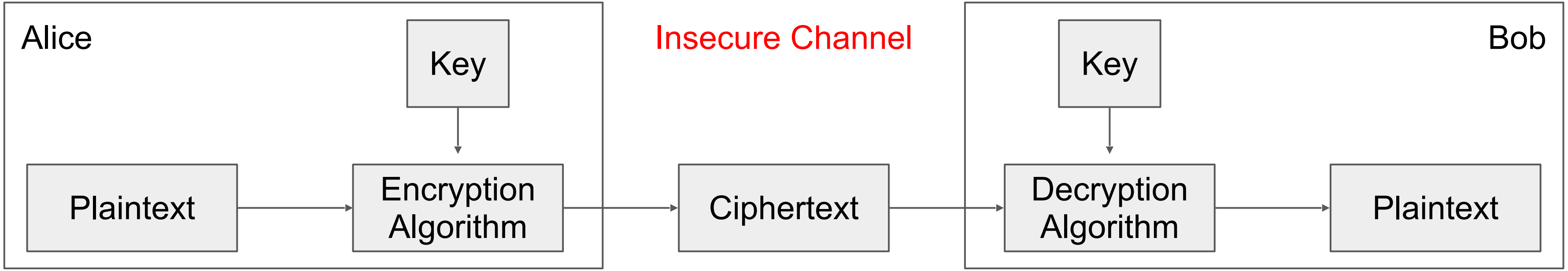
Symmetric-Key Encryption

- The next few schemes are symmetric-key encryption schemes
  - **Encryption schemes** aim to provide *confidentiality*
  - **Symmetric-key** means Alice and Bob share the same secret key that the attacker doesn’t know

- For modern schemes, we’re going to assume that messages are *bitstrings*
  - **Bitstring**: A sequence of bits (0 or 1), e.g. `11010101001001010`
  - Text, images, etc. can be converted into bitstrings before encryption, so bitstrings are a useful abstraction. After all, everything in a computer is just a sequence of bits!

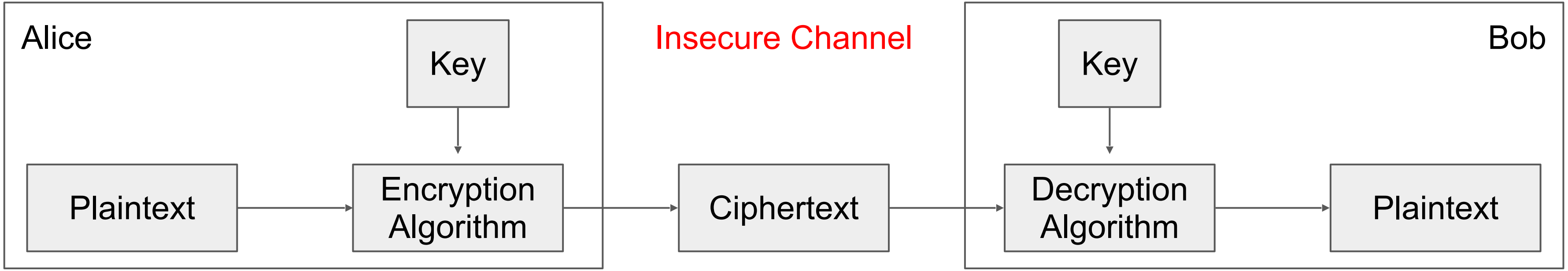
Symmetric-Key Encryption: Definition

- A symmetric-key encryption scheme has three algorithms:
  - KeyGen() → *K*: Generate a key *K*
  - Enc(*K*, *M*) → *C*: Encrypt a **plaintext** *M* using the key *K* to produce **ciphertext** *C*
  - Dec(*K*, *C*) → *M*: Decrypt a ciphertext *C* using the key *K*



Symmetric-Key Encryption: Definition

- What properties do we want from a symmetric encryption scheme?
  - **Correctness**: Decrypting a ciphertext should result in the message that was originally encrypted
    - Dec(K, Enc(K, M)) = M for all $K \leftarrow$ KeyGen() and M
  - **Efficiency**: Encryption/decryption algorithms should be fast: >1 Gbps on a standard computer
  - **Security**: Confidentiality



Defining Confidentiality

- Recall our definition of confidentiality from earlier: “An adversary cannot read our messages”
    - This definition isn’t very specific
        - What if Eve can read the first half of Alice’s message, but not the second half?
        - What if Eve figures out that Alice’s message starts with “Dear Bob”?
    - This definition doesn’t account for prior knowledge
        - What if Eve already knew that Alice’s message ends in “Sincerely, Alice”?
        - What if Eve knows that Alice’s message is “BUY!” or “SELL” but doesn't know which?

Q: How would you define confidentiality?

Defining Confidentiality

- A better definition of confidentiality: The ciphertext should not give the attacker *any additional information* about the plaintext.

- Let's design an experiment/security game to test our definition

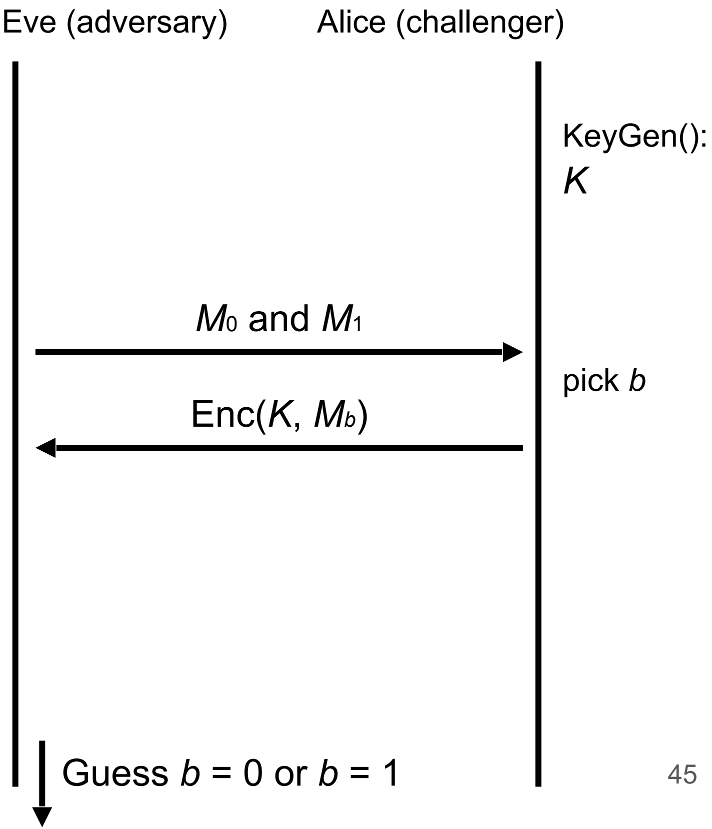
Security game: first attempt at confidentiality

1. Eve issues a pair of plaintexts M_0 and M_1 to Alice of the same length

2. Alice randomly chooses either M_0 or M_1 to encrypt and sends the encryption back
    a. Alice does not tell Eve which one was encrypted!

3. Eventually, Eve outputs a guess as to whether Alice encrypted M_0 or M_1

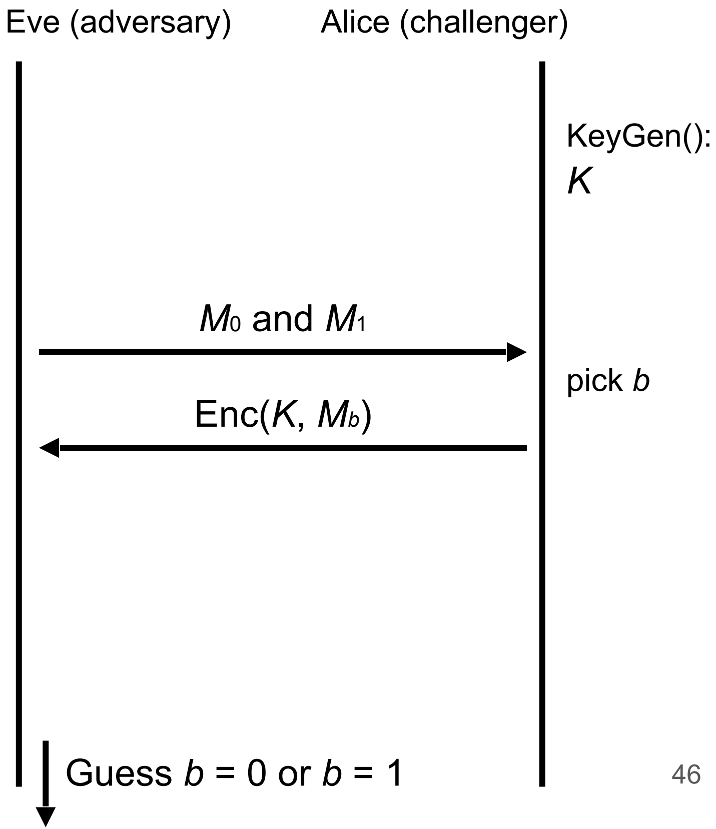
Q: If the scheme provides confidentiality, what chance does the attacker have to guess b?



Security game: intuition

- If the scheme is secure Eve can only guess with probability 1/2, which is no different than if Eve hadn't sent the ciphertext at all

- In other words: the ciphertext gave Eve no *additional* information about which plaintext was sent!



Defining Confidentiality: IND-CPA

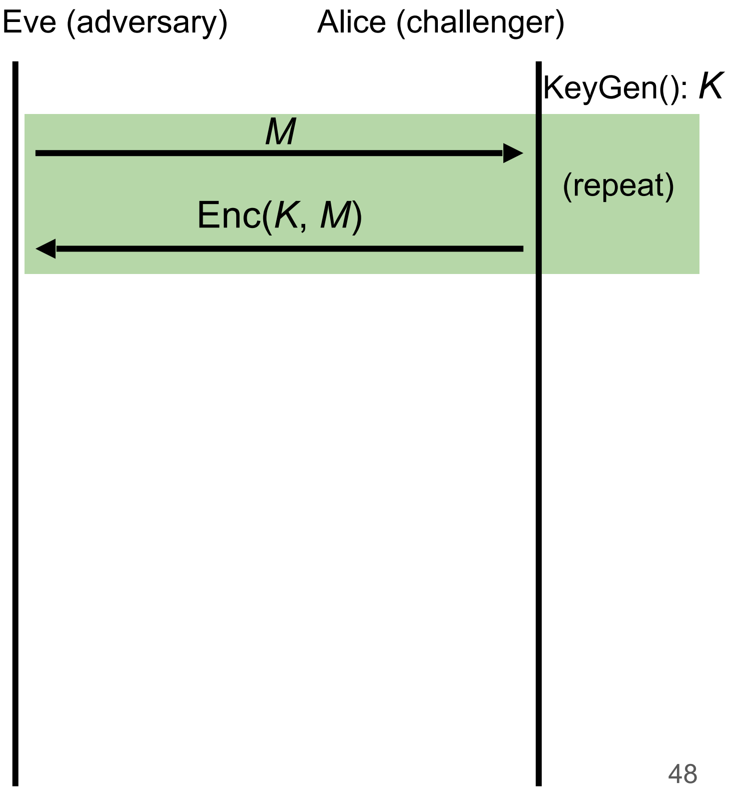
- Recall our threat model: Eve can also perform a **chosen plaintext attack**
    - Eve can trick Alice into encrypting arbitrary messages of Eve's choice
    - We can adapt our experiment to account for this threat model

- A better definition of confidentiality: Even if Eve is able to trick Alice into encrypting messages, Eve can still only guess what message Alice sent with probability 1/2.
    - This definition is called **IND-CPA** (indistinguishability under chosen plaintext attack)

- Cryptographic properties are often defined in terms of “games” that an adversary can either “win” or “lose”
    - We will use one to define confidentiality precisely

Defining Confidentiality: IND-CPA

1. Eve may choose plaintexts to send to Alice and receives their ciphertexts



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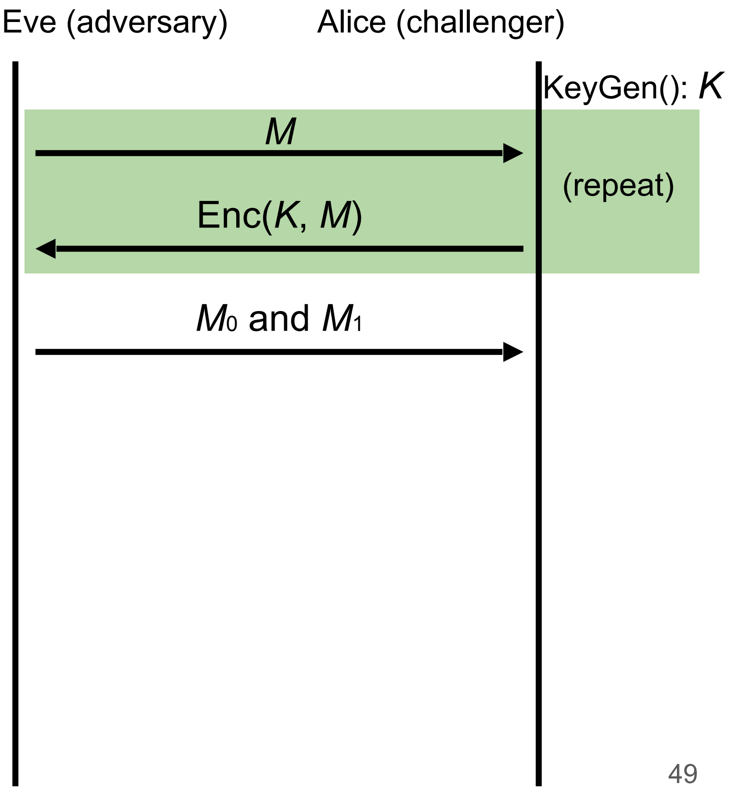

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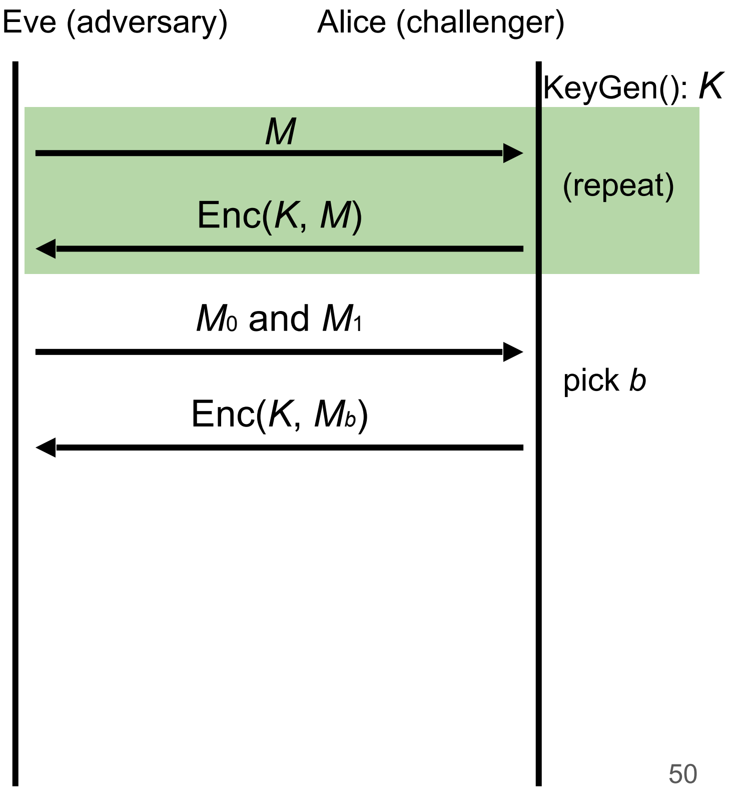

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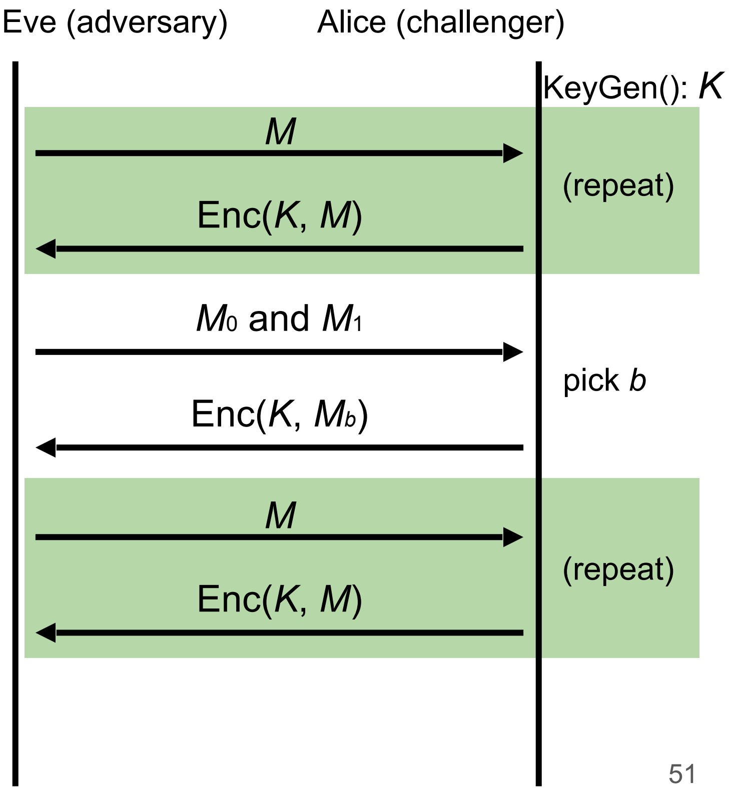
4. Eve may again choose plaintexts to send to Alice and receives their ciphertexts



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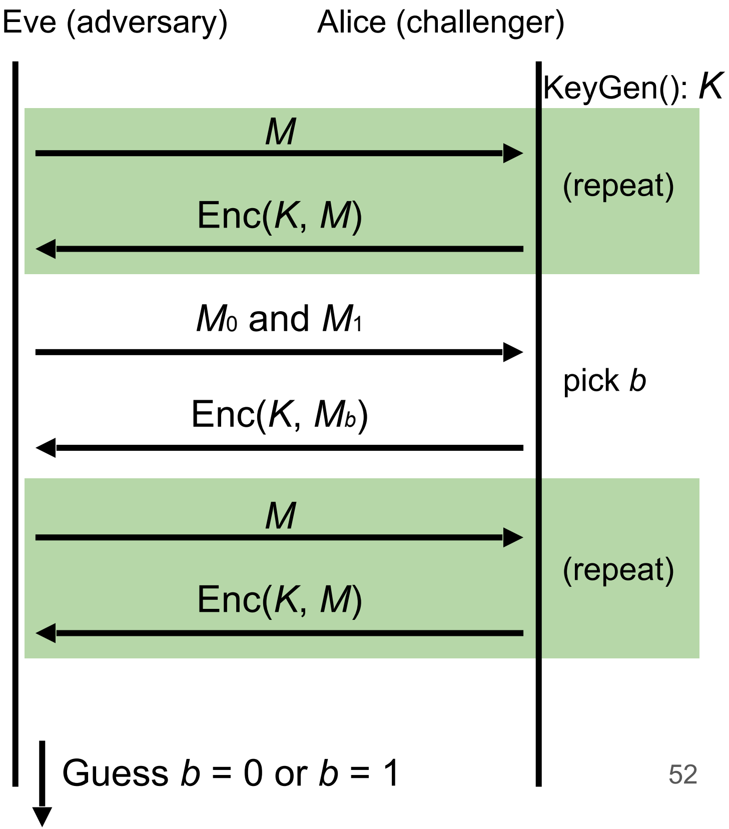


Defining Confidentiality: IND-CPA

- If Eve correctly guesses which message Alice encrypted, then Eve wins. Otherwise, she loses.

- How does Eve guess whether M_0 or M_1 was encrypted? What strategy does she use?
  - We don't *assume* she uses a particular strategy; Eve represents all possible strategies

- Proving insecurity: There exists at least *one* strategy that can win the IND-CPA game with probability > 1/2
  - 1/2 is the probability of winning by random guessing
  - If you can be better than random, then the ciphertext has leaked information, and Eve is able to learn it and use it to gain an advantage!

- Proving security: For *all* (polynomial-time) attackers/Eve-s, the probability of winning the IND-CPA game is at most ½+negl

Edge Cases: Length

- Cryptographic schemes are (usually) allowed to leak the length of the message
  - To hide length: All messages must always be the same length
  - Applications can choose to hide length by *padding* their own messages to the maximum possible length before encrypting

- In the IND-CPA game: M_0 and M_1 must be the same length
  - To break IND-CPA, Eve must learn something other than message length

Edge Cases: Attacker Runtime

- Some schemes are theoretically vulnerable, but secure in any real-world setting
    - If an attack takes longer than the life of the solar system to complete, it probably won't happen!

- In the IND-CPA game: Eve is limited to a practical runtime
    - One common practical limit: Eve is limited to polynomial runtime algorithms (no exponential-time algorithms)

Edge Cases: Negligible Advantage

- Sometimes it’s possible for Eve to win with probability $1/2 + 1/2^{128}$
  - This probability is greater than 1/2, but it's so close to 1/2 that it's as good as 1/2.
  - Eve's advantage is so small that she can't use it for any practical attacks
  - 2^{128} is larger than the total number of atoms in the universe

- In the IND-CPA game: The scheme is secure even if Eve can win with probability $\leq 1/2 + \varepsilon$, where ε is *negligible*
  - The actual mathematical definition of negligible is out of scope
  - Example: $1/2 + 1/2^{128}$: Negligible advantage
  - Example: 2/3: Non-negligible advantage

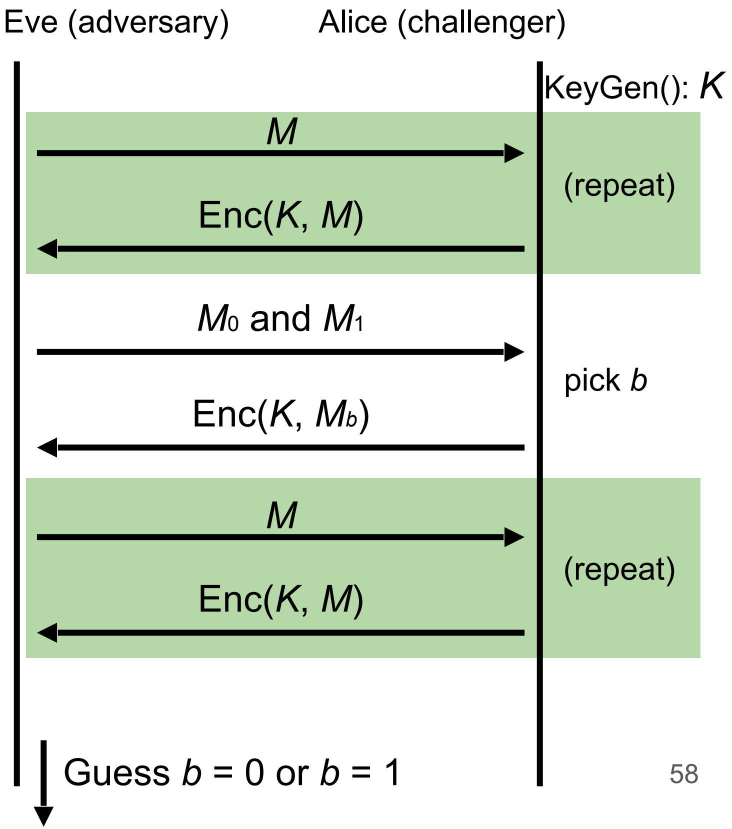
Edge Cases: Negligible Advantage

- Defining negligibility mathematically:
  - Advantage of the adversary should be exponentially small, based on the security parameters of the algorithm
  - Example: For an encryption scheme with a *k*-bit key, the advantage should be $O(1/2^k)$
- Defining negligibility practically:
  - A $1/2^{128}$ probability is currently unlikely
  - A $1/2^{20}$ probability is fairly likely
    - "One in a million events happen every day in New York City"
  - In between these extremes, it can be messy
    - Different algorithms run faster or slower and have their own security parameters
    - Computers get more powerful over time
    - Recall: Know your threat model!
- **Takeaway**: For now, 2^{80} is a reasonable threshold, but this will change over time!

IND-CPA: Putting it together

1. Eve may choose plaintexts to send to Alice and receives their ciphertexts
2. Eve issues a pair of plaintexts M_0 and M_1 to Alice
3. Alice randomly chooses either M_0 or M_1 to encrypt and sends the encryption back
   - Alice does not tell Eve which one was encrypted!
4. Eve may again choose plaintexts to send to Alice and receives their ciphertexts
5. Eventually, Eve outputs a guess as to whether Alice encrypted M_0 or M_1

- An encryption scheme is IND-CPA secure if fo polynomial time attackers Eve:
  - Eve can win with probability ≤ 1/2 + Ɛ, where Ɛ is *negligible.*



A Brief History of Cryptography

Cryptography by Hand: Caesar Cipher

- One of the earliest cryptographic schemes was the **Caesar cipher**
  - Used by Julius Caesar over 2,000 years ago
- KeyGen():
  - Choose a key *K* randomly between 0 and 25
- Enc(*K*, *M*):
  - Replace each letter in *M* with the letter *K* positions later in the alphabet
  - If *K* = 3, plaintext DOG becomes GRJ
- Dec(*K*, *C*):
  - Replace each letter in *C* with the letter *K* positions earlier in the alphabet
  - If *K* = 3, ciphertext GRJ becomes DOG

K = 3			
M	*C*	*M*	*C*
A	D	N	Q
B	E	O	R
C	F	P	S
D	G	Q	T
E	H	R	U
F	I	S	V
G	J	T	W
H	K	U	X
I	L	V	Y
J	M	W	Z
K	N	X	A
L	O	Y	B
M	P	Z	C

Cryptography by Hand: Attacks on the Caesar Cipher

- Eve sees the ciphertext JCKN ECGUCT, but doesn’t know the key *K*
- If you were Eve, how would you try to break this algorithm?
- Brute-force attack: Try all 26 possible keys!
- Use existing knowledge: Assume that the message is in English

+1	IBJM DBFTBS
+2	HAIL CAESAR
+3	GZHK BZDRZQ
+4	FYGJ AYCQYP
+5	EXFI ZXBPXO
+6	DWEH YWAOWN
+7	CVDG XVZNVM
+8	BUCF WUYMUL
+9	ATBE VTXLTK
+10	ZSAD USWKSJ
+11	YRZC TRVJRI
+12	XQYB SQUIQH
+13	WPXA RPTHPG
+14	VOWZ QOSGOF
+15	UNVY PNRFNE
+16	TMUX OMQEMD
+17	SLTW NLPDLC
+18	RKSV MKOCKB
+19	QJRU LJNBJA
+20	PIQT KIMAIZ
+21	OHPS JHLZHY
+22	NGOR IGKYGX
+23	MFNQ HFJXFW
+24	LEMP GEIWEV
+25	KDLO FDHVDU

Cryptography by Hand: Attacks on the Caesar Cipher

- Eve sees the ciphertext JCKN ECGUCT, but doesn't know the key *K*
- Chosen-plaintext attack: Eve tricks Alice into encrypting plaintext of her choice
    - Eve sends a message *M* = AAA and receives *C* = CCC
    - Eve can deduce the key: C is 2 letters after A, so *K* = 2
    - Eve has the key, so she can decrypt the ciphertext

Cryptography by Hand: Substitution Cipher

- A better cipher: create a mapping of each character to another character.
  - Example: A = N, B = Q, C = L, D = Z, etc.
  - Unlike the Caesar cipher, the shift is no longer constant!
- KeyGen():
  - Generate a random, one-to-one mapping of characters
- Enc(*K*, *M*):
  - Map each letter in *M* to the output according to the mapping *K*
- Dec(*K*, *C*):
  - Map each letter in *C* to the output according to the *reverse* of the mapping *K*

K			
M	*C*	*M*	*C*
A	N	N	G
B	Q	O	P
C	L	P	T
D	Z	Q	A
E	K	R	J
F	R	S	O
G	V	T	D
H	U	U	I
I	E	V	C
J	S	W	F
K	B	X	M
L	W	Y	X
M	Y	Z	H

Cryptography by Hand: Attacks on Substitution Ciphers

- Does the brute-force attack still work?
  - There are 26! ≈ 2^{88} possible mappings to try
    - Too much for most modern computers… for now
- How about the chosen-plaintext attack?
  - Trick Alice into encrypting ABCDEFGHIJKLMNOPQRSTUVWXYZ, and you'll get the whole mapping!
- Another strategy: *cryptanalysis*
  - The most common english letters in text are E, T, A, O, I, N

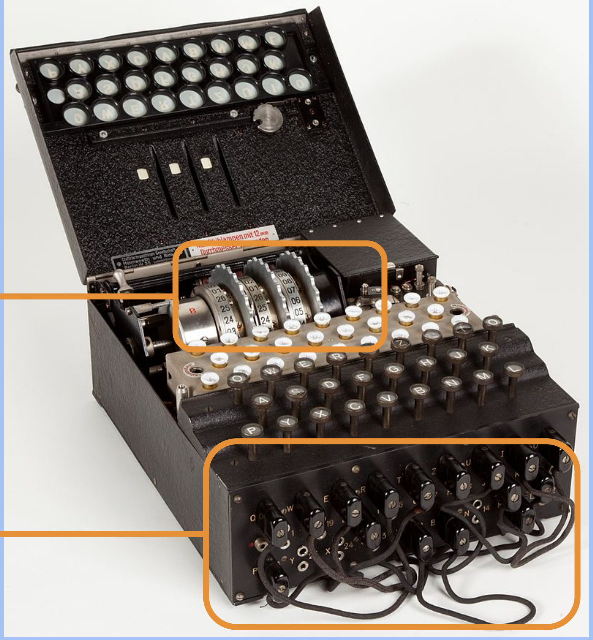
K			
M	*C*	*M*	*C*
A	N	N	G
B	Q	O	P
C	L	P	T
D	Z	Q	A
E	K	R	J
F	R	S	O
G	V	T	D
H	U	U	I
I	E	V	C
J	S	W	F
K	B	X	M
L	W	Y	X
M	Y	Z	H

Takeaways

- Cryptography started with paper-and-pencil algorithms (Caesar cipher)
- Then cryptography moved to machines (Enigma)
- Finally, cryptography moved to computers (which we're about to study)
- Hopefully you gained some intuition for some of the cryptographic definitions

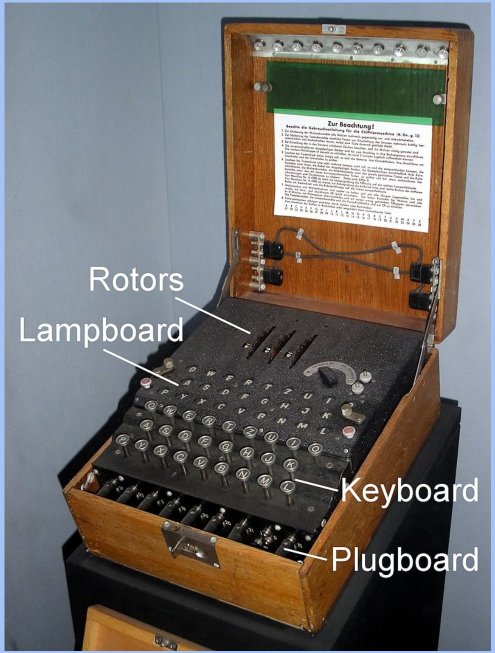
Cryptography by Machines: Enigma

- A mechanical encryption machine used by the Germans in WWII



Rotors

Plugboard

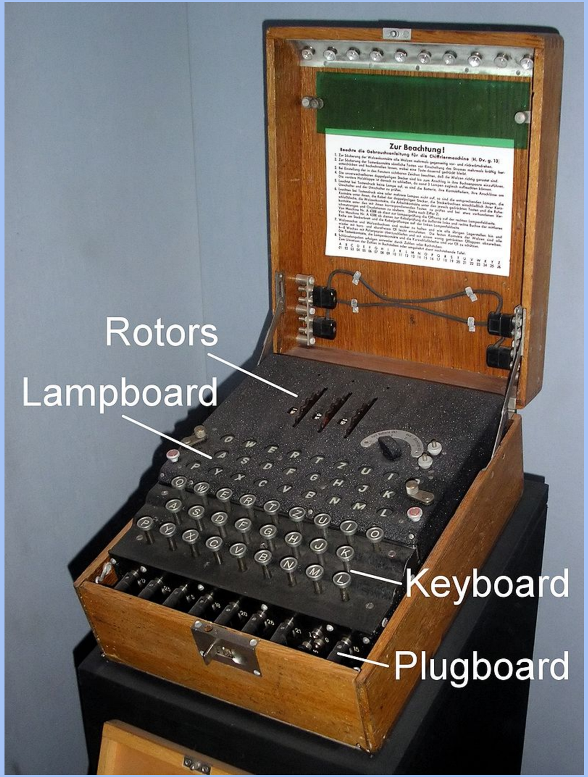


Enigma Operating Principle: Rotor Machine

- The encryption core was composed of 3 or 4 rotors
    - Each rotor was a fixed permutation (e.g. A maps to F, B maps to Q...)
    - And the end was a "reflector", a rotor that sent things backwards
    - Plus a fixed-permutation plugboard
- A series of rotors were arranged in a sequence
    - Each keypress would generate a current from the input to one light for the output
    - Each keypress also advanced the first rotor
        - When the first rotor makes a full rotation, the second rotor advances one step
        - When the second rotor makes a full rotation, the third rotor advances once step

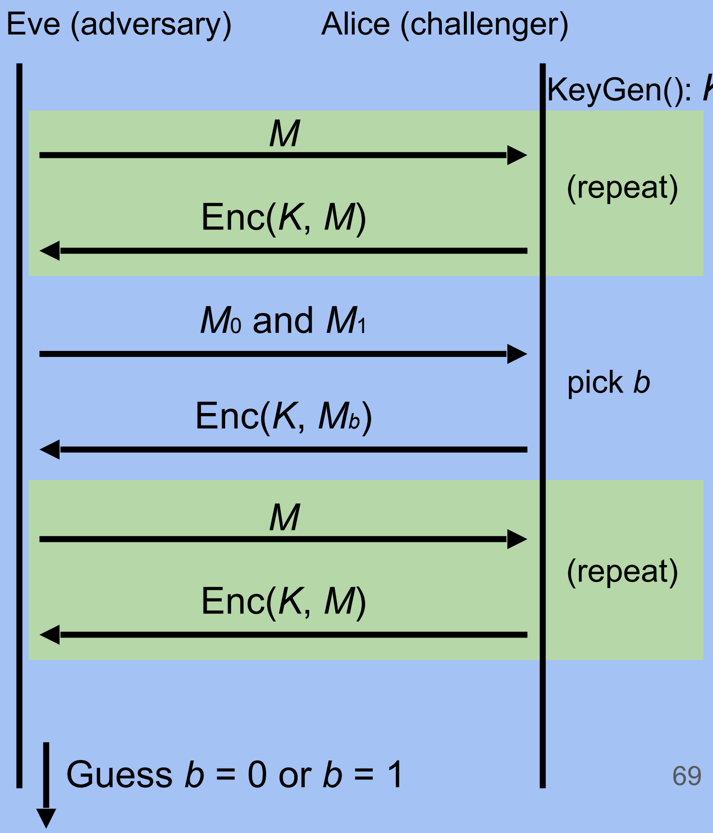
Cryptography by Machines: Enigma

- KeyGen():
  - Choose rotors, rotor orders, rotor positions, and plugboard settings
  - 158,962,555,217,826,360,000 possible keys
- Enc(*K*, *M*) and Dec(*K*, *C*):
  - Input the rotor settings *K* into the Enigma machine
  - Press each letter in the input, and the lampboard will light up the corresponding output letter
  - Encryption and decryption are the same algorithm!
- Germans believed that Enigma was an “unbreakable code”



Cryptography by Machines: Enigma

- Enigma has a significant weakness: a letter never maps to itself!
  - No rotor maps a letter to itself
  - The reflector never maps a letter to itself
  - This property is necessary for Enigma's mechanical system to work
- What pair of messages should Eve send to Alice in the challenge phase?
  - Send $M_0 = A^k$, $M_1 = B^k$
  - M_0 is a string of k 'A' characters, M_1 is a string of k 'B' characters
- How can Eve probably know which message Alice encrypted?
  - If there are no 'A' characters, it was M_0
  - If there are no 'B' characters, it was M_1



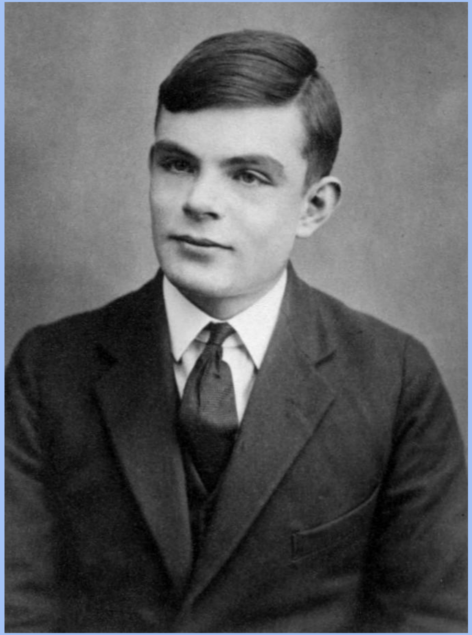
Cryptography by Machines: Attack on Enigma

- Polish and British cryptographers built BOMBE, a machine to brute-force Enigma keys
- Why was Enigma breakable?
  - Kerckhoff’s principle: The Allies stole Enigma machines, so they knew the algorithm
  - Known plaintext attacks: the Germans often sent predictable messages (e.g. the weather report every morning)
  - Chosen plaintext attacks: the Allies could trick the Germans into sending a message (e.g. “newly deployed minefield”)
  - Brute-force: BOMBE would try many keys until the correct one was found
    - Plus a weakness: You'd be able to try multiple keys with the same hardware configuration

BOMBE machine

Cryptography by Machines: Legacy of Enigma

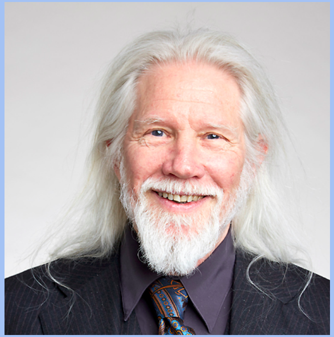
- Alan Turing, one of the cryptographers who broke Enigma, would go on to become one of the founding fathers of computer science
- Most experts agree that the Allies breaking Enigma shortened the war in Europe by about a year



Alan Turing

Cryptography by Computers

- The modern era of cryptography started after WWII, with the work of Claude Shannon
- “New Directions in Cryptography” (1976) showed how number theory can be used in cryptography
  - Its authors, Whitfield Diffie and Martin Hellman, won the Turing Award in 2015 for this paper
- This is the era of cryptography we’ll be focusing on



One of these is Diffie, and the other one is Hellman.