Thus far, we have <u>assumed</u> that parties have a <u>shared</u> key. Where does the shared key come from?

Can we do this using the tools we have developed so far?

So far in this course:

$$\text{OWFs} \Rightarrow \text{PRGs} \Rightarrow \text{PRFs} \begin{array}{l} \nearrow \text{CPA-secure encryption} \\ \searrow \text{MAC} \end{array} \Rightarrow \text{authenticated encryption}$$

Can we show OWFs (or even OWPs) $\Rightarrow$ key agreement?

Key agreement:

Alice $\quad\quad$ Bob

$\longrightarrow$

$\longleftarrow$

$\vdots$

$\longrightarrow$

$\longleftarrow$

$\downarrow$ k_1 $\quad\quad$ $\downarrow$ k_2

Requirements:
1) $k_1 = k_2 = k$ with high probability
2) Eavesdropper cannot learn k (efficiently)

<u>Merkle puzzles</u>: Suppose $f : \mathcal{X} \to \mathcal{Y}$ is an injective one-way function

<u>Alice</u> $\quad\quad\quad\quad$ <u>Bob</u>

$x_1, \dots, x_n \leftarrow \mathcal{X}$

$\xrightarrow{y_1 = f(x_1), \dots, y_n = f(x_n)}$

$i \xleftarrow{R} [n]$

find x_i such that $f(x_i) = y_i$ [solve the "puzzle"]

$\xleftarrow{\text{Encrypt}_{AE}(k, m)}$

derive a key k from x_i

(e.g., using hard-core bit or hash the input) — modeled as random oracle

$\downarrow$

try each key k_i to decrypt ciphertext — derived from x_i

Suppose it takes time t to solve a puzzle. Adversary needs time $O(nt)$ to solve all puzzles and identify key. Honest parties work in time $O(n + t)$.

$\hookrightarrow$ Only provides <u>linear gap</u> between honest parties and adversary

Can we get a super-polynomial gap just using OWFs? Very difficult! [Impagliazzo-Rudich]

Can we get a super-linear gap just using OWFs? Very difficult! [Barak-Mahmoody]

$\hookrightarrow$ A positive result will require non-black-box techniques.

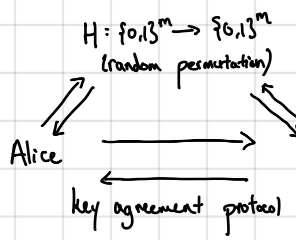
Impagliazzo-Rudich: Proving the existence of key-agreement that makes black-box use of OWPs implies $P \neq NP$.

Intuition: Black-box construction means key-agreement protocol only needs oracle access to one-way permutation (does not depend on the code of the OWP)

- Namely, given OWP f, there is a key-agreement protocol Π^f that is a key-agreement protocol (and security reduction also uses f as black box)

  construction Π can make oracle queries to f (only way to interact with f is through queries)

- In a world where $P = NP$, secure key agreement is impossible
  (intuition: eavesdropper can guess internal state of one of the parties)
- Impossibility holds even if parties have access to a random permutation oracle



  - without loss of generality, suppose Alice/Bob may one query to H and then send a message and overall protocol is n rounds
  - observation: if Alice queries H on x, but Bob does not, then secret cannot depend on x (since Bob's view is essentially independent of $H(x)$).
  - to break key agreement, adversary has to guess intersection queries made by both Alice and Bob
  - on each round, adversary samples many executions of protocol that is consistent with Alice's / Bob's communication transcript (and previous simulated queries)
  - [IR89]: with high probability, adversary will identify all intersection queries made by Alice and Bob $\Rightarrow$ breaks key exchange
- In a world with a random permutation oracle, one-way permutations exist unconditionally
  ↳ And if there was a black-box construction of key exchange from OWP, then secure key exchange is also possible in this model $\Rightarrow P \neq NP$.
- Conclusion: Proving a statement like OWP/OWF $\overset{\text{black-box}}{\Longrightarrow}$ secure key exchange will prove that $P \neq NP$

- This is an example of a black-box separation.

  Open Problem: Secure key exchange via non-black-box use of OWFs/OWPs?

- Black-box separations also known for many other notions:
  e.g., Simon: black-box separation between one-way permutations and CRHFs

Implication of black-box separations: Constructing secure key agreement will require more than just one-way functions

↳ Distinction between Minicrypt and Cryptomania in "Impagliazzo's five worlds"

We will turn to algebra/number theory for new sources of hardness to build key agreement protocols.

Definition. A group consists of a set $\mathbb{G}$ together with an operation $*$ that satisfies the following properties:

- Closure: If $g_1, g_2 \in \mathbb{G}$, then $g_1 * g_2 \in \mathbb{G}$
- Associativity: For all $g_1, g_2, g_3 \in \mathbb{G}$, $g_1 * (g_2 * g_3) = (g_1 * g_2) * g_3$
- Identity: There exists an element $e \in \mathbb{G}$ such that $e * g = g = g * e$ for all $g \in \mathbb{G}$
- Inverse: For every element $g \in \mathbb{G}$, there exists an element $g^{-1} \in \mathbb{G}$ such that $g * g^{-1} = e = g^{-1} * g$

In addition, we say a group is commutative (or abelian) if the following property also holds:

- Commutative: For all $g_1, g_2 \in \mathbb{G}$, $g_1 * g_2 = g_2 * g_1$

called "multiplicative" notation

Notation: Typically, we will use "$\cdot$" to denote the group operation (unless explictly specified otherwise). We will write g^x to denote $\underbrace{g \cdot g \cdot g \cdots g}_{x \text{ times}}$ (the usual exponential notation). We use "1" to denote the multiplicative identity

Examples of groups: $(\mathbb{R}, +)$: real numbers under addition

$(\mathbb{Z}, +)$: integers under addition

$(\mathbb{Z}_p, +)$: integers modulo p under addition [sometimes written as $\mathbb{Z}/p\mathbb{Z}$]

here, p is prime

The structure of $\mathbb{Z}_p^*$ (an important group for cryptography):

$$\mathbb{Z}_p^* = \{x \in \mathbb{Z}_p : \text{there exists } y \in \mathbb{Z}_p \text{ where } xy = 1 \pmod p\}$$

↖ the set of elements with multiplicative inverses modulo p

What are the elements in $\mathbb{Z}_p^*$?

greatest common divisor

<u>Bezout's identity</u>: For all positive integers $x, y \in \mathbb{Z}$, there exists integers $a, b \in \mathbb{Z}$ such that $ax + by = \gcd(x, y)$.

<u>Corollary</u>: For prime p, $\mathbb{Z}_p^* = \{1, 2, \dots, p-1\}$.

<u>Proof.</u> Take any $x \in \{1, 2, \dots, p-1\}$. By Bezout's identity, $\gcd(x, p) = 1$ so there exists integers $a, b \in \mathbb{Z}$ where $1 = ax + bp$.
Modulo p, this is $ax = 1 \pmod p$ so $a = x^{-1} \pmod p$.

Coefficients a, b in Bezout's identity can be efficiently computed using the extended Euclidean algorithm:

<u>Euclidean algorithm</u>: algorithm for computing $\gcd(a, b)$ for positive integers $a > b$:
relies on fact that $\gcd(a, b) = \gcd(b, a \pmod b)$:
to see this: take any $a > b$
↳ we can write $a = b \cdot q + r$ where $q \geq 1$ is the quotient and $0 \leq r < b$ is the remainder
↳ d divides a and b $\iff$ d divides b and r
↳ $\gcd(a, b) = \gcd(b, r) = \gcd(b, a \pmod b)$
gives an explicit algorithm for computing gcd: repeatedly divide:

$\gcd(60, 27)$:

$$60 = 27(2) + 6 \qquad [q = 2, r = 6] \rightsquigarrow \gcd(60, 27) = \gcd(27, 6)$$
$$27 = 6(4) + 3 \qquad [q = 4, r = 3] \rightsquigarrow \gcd(27, 6) = \gcd(6, 3)$$
$$6 = 3(2) + 0 \qquad [q = 2, r = 0] \rightsquigarrow \gcd(6, 3) = \gcd(3, 0) = 3$$

"rewind" to recover coefficients in Bezout's identity:

extended Euclidean algorithm
$$\left\{ \begin{array}{l} 60 = 27(2) + 6 \\ 27 = 6(4) + 3 \\ 6 = 3(2) + 0 \end{array} \right. \longrightarrow 3 = 27 - 6 \cdot 4$$

$$6 = 60 - 27(2)$$
$$27 - (60 - 27(2))4$$
$$= 27(9) + 60(-4)$$

coefficients

<u>Iterations needed</u>: $O(\log a)$ — i.e., bit-length of the input [worst case inputs: Fibonacci numbers]

<u>Implication</u>: Euclidean algorithm can be used to compute modular inverses (faster algorithms also exist)