

Lecture 05: Repeated Squaring

- Let $(G, \circ)$ be a group with generator g
- We define $g^0 = e$, where $e \in G$ is the identity element of G
- We define $g^i = \overbrace{g \circ g \circ \cdots \circ g}^{i\text{-times}}$
- For example, the group $(\mathbb{Z}_7^*, \times)$ is generated by 3 but not 2

Motivation of Efficient Algorithm to Compute Exponentiation

- Suppose p is a prime number that is represented using 1000-bits
- Note that the number p is in the range $[2^{999}, 2^{1000})$. We shall summarize this by stating that p is roughly (in the order of) 2^{1000} .
- Suppose we are interested to work on the field $(\mathbb{Z}_p^*, \times)$ with generator g
- Given input $i \in \{0, 1, \dots, p-1\}$, we are interested in computing $g^i \in \mathbb{Z}_p^*$

First Attempt

Exp (i):

- ① $\text{prod} = e$
- ② For index in the range $\{1, \dots, i\}$:
 - ① $\text{prod} = \text{prod} \circ g$
- ③ Return prod

- Note that this algorithm runs the inner loop i times. The number i can take values $\{0, 1, \dots, p-2\}$. For example, if $i \geq 2^{500}$ then the algorithm will run the inner loop more than the number of atoms in the universe. Effectively, the algorithm is useless
- The algorithm takes $O(i)$ run-time. The size of the input i is $\log i$. So, this algorithm is an exponential time algorithm

Exp (i):

- ① If $i = 0$: Return e
- ② If i is even:
 - ① $\alpha = \text{Exp}(i/2)$
 - ② Return $\alpha \circ \alpha$
- ③ If i is odd:
 - ① $\alpha = \text{Exp}((i - 1)/2)$
 - ② Return $\alpha \circ \alpha \circ g$

- Note that the argument to Exp becomes smaller by one-bit in recursive call. So, the algorithm performs (at most) 1000 recursive call. This is an efficient algorithm because it runs in time $O(\log i)$

A Few Optimizations.

- Testing whether i is even or not can be performed by computing $i \& 1$ (here, $\&$ is the bit-wise and of the binary representation of i and 1)
- Computing $(i/2)$ when i is even, or computing $(i - 1)/2$ when i is odd can be achieved by $i \gg 1$ (that is, right-shift the binary representation of i by one position)

The code shall look as follows

Exp (i):

① If $i = 0$: Return e

② $j \gg 1$

③ If $(i \& 1) == 0$:

① $\alpha = \text{Exp}(j)$

② Return $\alpha \circ \alpha$

④ else:

① $\alpha = \text{Exp}(j)$

② Return $\alpha \circ \alpha \circ g$

- 1 The algorithm makes recursive calls. Can we further optimize and avoid recursive function calls? That is, can we unroll the recursion into a for loop?

In the following code, we assume that we represent the prime p using t -bits. For example, we were considering $t = 1000$ in the ongoing example.

We perform a preprocessing step to compute the following global variables.

Global Preprocessing.

- ① For index in the set $\{0, 1, \dots, t-1\}$:
 - ① If index == 0: $\alpha_{\text{index}} = g$ and $c_{\text{index}} = 1$
 - ② Else: $\alpha_{\text{index}} = \alpha_{\text{index}-1} \circ \alpha_{\text{index}-1}$ and $c_{\text{index}} = (c_{\text{index}-1} \ll 1)$

- Note that $\alpha_{\text{index}} = g^{2^{\text{index}}}$, for all $\text{index} \in \{0, 1, \dots, t-1\}$
- Further, note that $c_{\text{index}} = 2^{\text{index}}$, for all $\text{index} \in \{0, 1, \dots, t-1\}$

We shall use the preprocessed data to compute the exponentiation

Exp (i):

- ① $\text{prod} = e$
- ② For index in the set $\{0, 1, \dots, t - 1\}$:
 - ① If $(i < c_{\text{index}})$: Break
 - ② If $(i \& c_{\text{index}}) \neq 0$: $\text{prod} = \text{prod} \circ \alpha_{\text{index}}$
- ③ Return prod

- Note that the test “the $(1 + \text{index})$ -th bit in the binary representation of i is 1” is identical to the test $(i \& c_{\text{index}}) \neq 0$
- If this test passes, then prod is multiplied by $\alpha_{\text{index}} = g^{2^{\text{index}}}$
- Prove: This approach correctly calculates g^i
- Note that the runtime is $O(\log i)$ (that is, the algorithm is efficient)

- Let us consider a problem that shall use all the facts we studied about groups and fields in the last two lectures. There are multiple solutions with varying degree of complexities
- Compute

$$17^{2020} \bmod 23$$

Solution 1.

- We can use repeated squaring directly to compute

$$17^1 \mod 23$$

$$17^2 \mod 23$$

$$17^4 \mod 23$$

$$\vdots$$

$$17^{1024} \mod 23$$

- Write 2020 in binary and compute $17^{2020} \mod 23$ using the values computed above
- Although this is a correct and a tractable way to compute this value, it is computationally intensive and prone to errors (without a calculator)

Solution 2.

- In homework you will prove that $x^p = x \pmod p$, where p is a prime and x is any integer
- You can use this fact to simplify the computation of $17^{2020} \pmod{23}$ as follows

$$\begin{aligned}
 17^{2020} \bmod 23 &= 17^{23} \cdot 17^{1997} \bmod 23 \\
 &= \left(17^{23}\right)^2 \cdot 17^{1974} \bmod 23 \\
 &\quad \vdots \\
 &= \left(17^{23}\right)^{87} \cdot 17^{19} \bmod 23 \\
 &= (17)^{87} \cdot 17^{19} \bmod 23, \quad \text{using } x^p = x \bmod p \\
 &= 17^{106} \bmod 23 \\
 &= \left(17^{23}\right)^4 \cdot 17^{14} \bmod 23 \\
 &= (17)^4 \cdot 17^{14} \bmod 23, \quad \text{using } x^p = x \bmod p \\
 &= 17^{18} \bmod 23
 \end{aligned}$$

- This final expression can be computed using the repeated squaring technique

Solution 3.

- In homework you will prove that $x^{p-1} = 1 \pmod p$, where p is a prime and x is any integer NOT divisible by p (there are also alternate proofs of this statement by considering the size of the subgroup of $(\mathbb{Z}_p^*, \times)$ that is generated by x)
- So, we can compute the expression as follows

$$\begin{aligned}
 17^{2020} \pmod{23} &= 17^{22} \cdot 17^{1998} \pmod{23} \\
 &= (17^{22})^2 \cdot 17^{1976} \pmod{23} \\
 &\vdots \\
 &= (17^{22})^{91} \cdot 17^{18} \pmod{23} \\
 &= (1)^{91} \cdot 17^{18} \pmod{23}, && \text{using } x^{p-1} = 1 \pmod p \\
 &= 17^{18} \pmod{23}
 \end{aligned}$$

- BTW, in general you can conclude that

$$x^n = x^{n \bmod p-1} \bmod p,$$

for any integer n and any integer x that is not divisible by p

- Now you can compute $17^{18} \bmod 23$ result using repeated squaring technique

$$17^1 = 17 \bmod 23$$

$$17^2 = 13 \bmod 23$$

$$17^4 = 8 \bmod 23$$

$$17^8 = 18 \bmod 23$$

$$17^{16} = 2 \bmod 23$$

- Now, we have

$$\begin{aligned} 17^{18} &= 17^{16+2} \mod 23 \\ &= 17^{16} \cdot 17^2 \mod 23 \\ &= 2 \cdot 13 \mod 23 \\ &= 3 \mod 23 \end{aligned}$$

- Therefore, we conclude that

$$17^{2020} = 17^{18} = 3 \mod 23.$$

That is our answer!