

Hashing: Hash Functions

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Data Structures Fundamentals
Algorithms and Data Structures

Outline

- 1 Phone Book Data Structure
- 2 Universal Family
- 3 Hashing Phone Numbers
- 4 Hashing Names
- 5 Analysis of Polynomial Hashing

Phone Book

Design a data structure to store your contacts: names of people along with their phone numbers. The following operations should be fast:

- Add and delete contacts,
- Call person by name,
- Determine who is calling given their phone number.

- We need two Maps:
(phone number \rightarrow name) and
(name \rightarrow phone number)

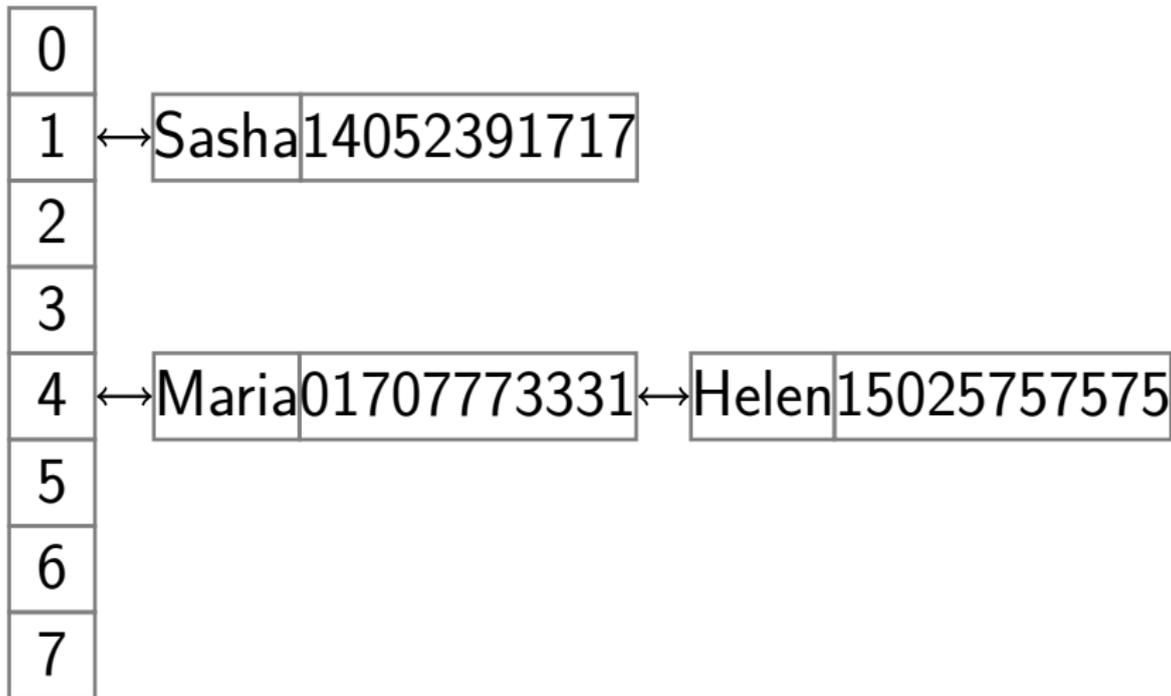
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(name \rightarrow phone number)
- Implement these Maps as hash tables
- First, we will focus on the Map from
phone numbers to names

Chaining for Phone Book

- Select hash function h of cardinality m
- Create array `Chains` of size m
- Each element of `Chains` is a list of pairs `(name, phoneNumber)`, called *chain*
- Pair `(name, phoneNumber)` goes into chain at position $h(\text{ConvertToInt}(\text{phoneNumber}))$ in the array `Chains`

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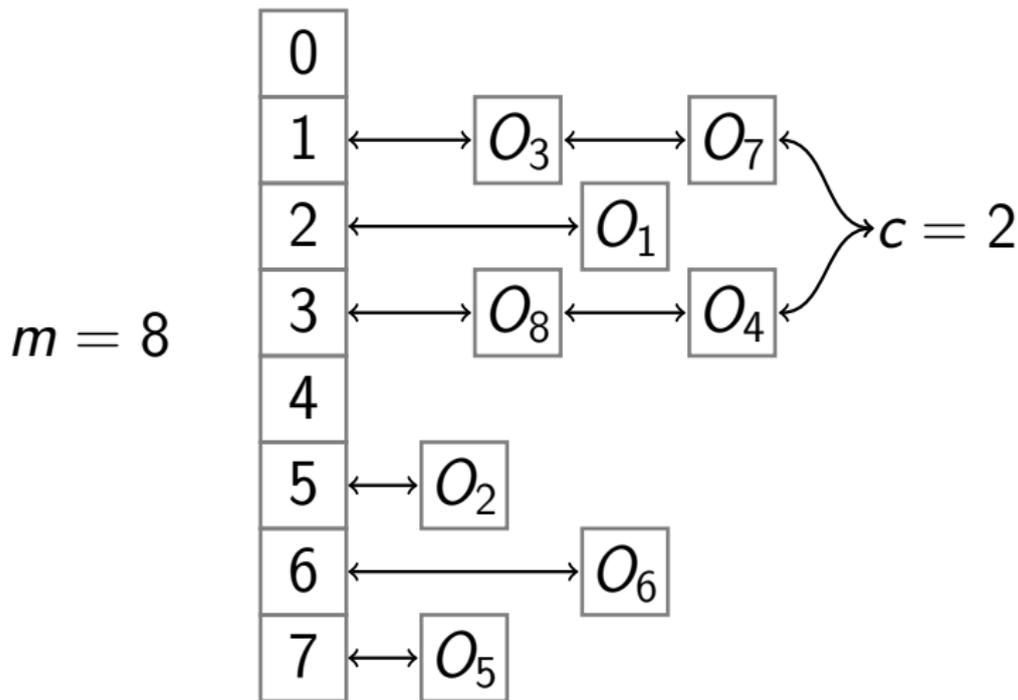
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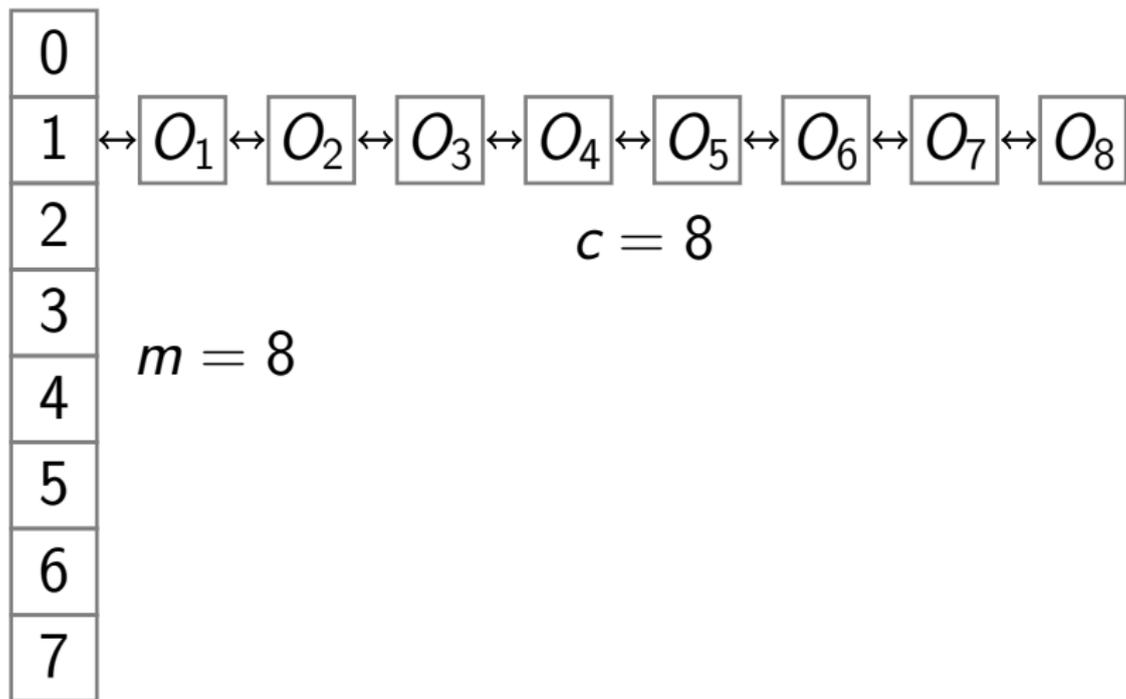
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- $\Theta(n + m)$ memory is used
- Operations run in time $\Theta(c + 1)$
- You want small m and $c!$ (but $c \geq \frac{n}{m}$)

Good Example



Bad Example



First Digits

- For the map from phone numbers to names, select $m = 1000$

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- $h(800-123-45-67) = 800$
- **Problem: area code**
- $h(425-234-55-67) =$
 $h(425-123-45-67) =$
 $h(425-223-23-23) = \dots = 425$

Last Digits

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- $h(800-123-45-67) = 567$
- Problem if many phone numbers end with three zeros

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- Hash function must be deterministic

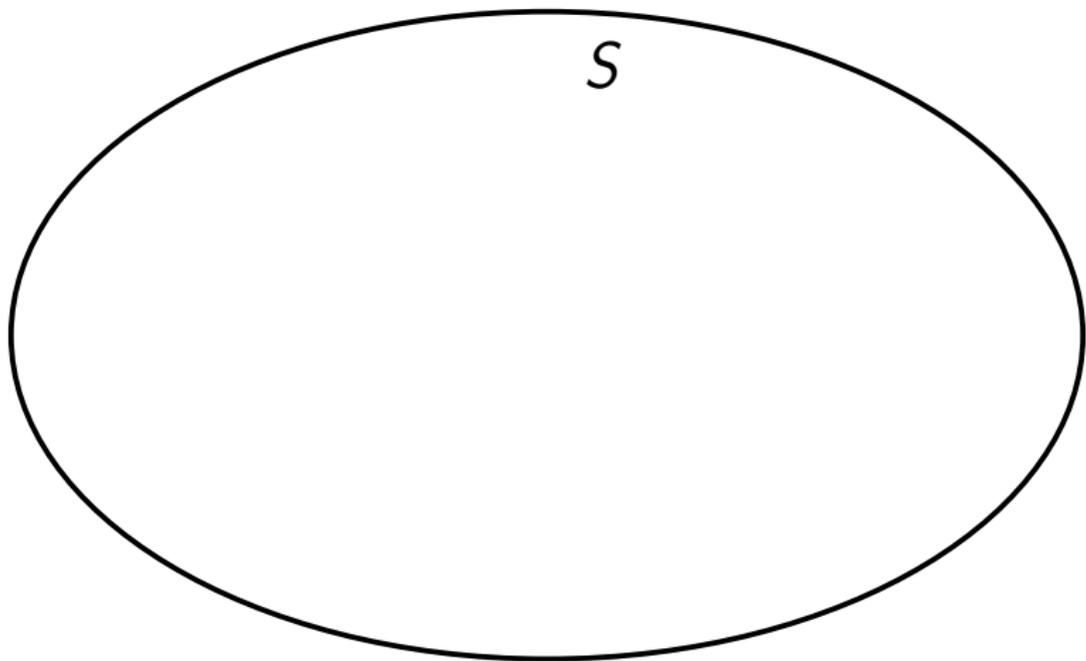
Good Hash Functions

- Deterministic
- Fast to compute
- Distributes keys well into different cells
- Few collisions

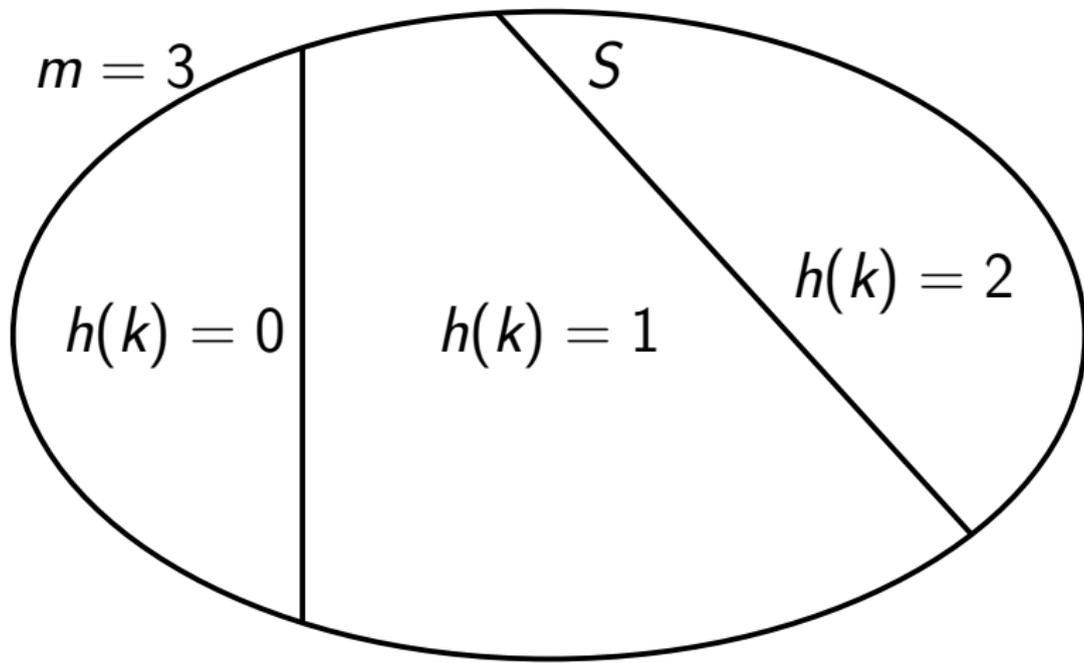
No Universal Hash Function

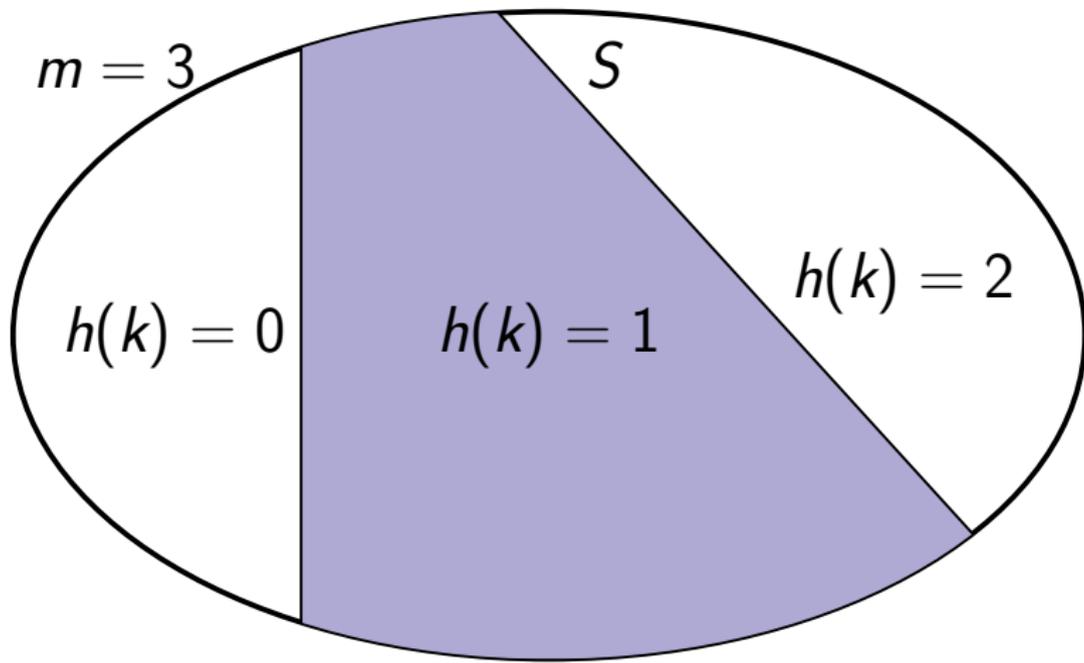
Lemma

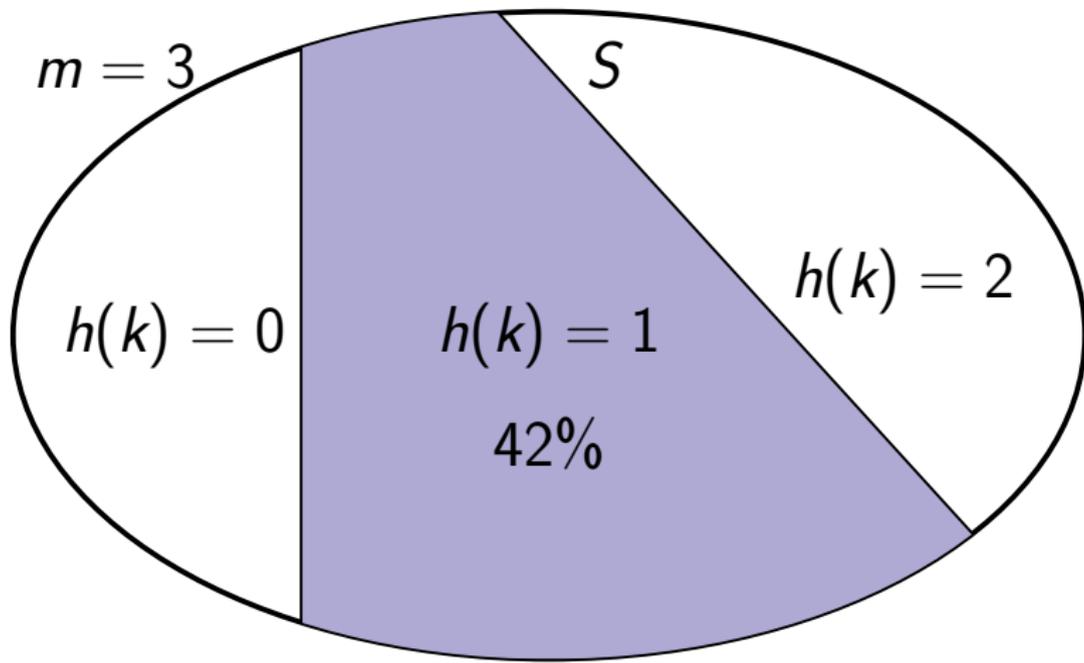
If the number of possible keys is big ($|S| \gg m$), for any hash function h there is a bad input resulting in many collisions.



S







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Universal Family

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Let U be the **universe** — the set of all possible keys.

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Let U be the **universe** — the set of all possible keys. A set of hash functions

$$\mathcal{H} = \{h : U \rightarrow \{0, 1, 2, \dots, m - 1\}\}$$

is called a **universal family** if for any two keys $x, y \in U, x \neq y$ the probability of **collision**

$$\Pr[h(x) = h(y)] \leq \frac{1}{m}$$

Universal Family

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means that a collision $h(x) = h(y)$ for any **fixed** pair of different keys x and y happens for no more than $\frac{1}{m}$ of all hash functions $h \in \mathcal{H}$.

How Randomization Works

- $h(x) = \text{random}(\{0, 1, 2, \dots, m - 1\})$
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- Select a random function h from \mathcal{H}
- Fixed h is used throughout the algorithm

Load Factor

Definition

The ratio $\alpha = \frac{n}{m}$ between number of objects n stored in the hash table and the size of the hash table m is called **load factor**.

Running Time

Lemma

If h is chosen randomly from a **universal family**, the average length of the longest chain c is $O(1 + \alpha)$, where $\alpha = \frac{n}{m}$ is the **load factor** of the hash table.

Corollary

*If h is from **universal family**, operations with hash table run on average in time $O(1 + \alpha)$.*

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- Use $O(m) = O(\frac{n}{\alpha}) = O(n)$ memory to store n keys
- Operations run in time $O(1 + \alpha) = O(1)$ on average

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Dynamic Hash Tables

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- Copy the idea of dynamic arrays!
- Resize the hash table when α becomes too large
- Choose new hash function and **rehash** all the objects

Rehashing

Keep load factor below 0.9:

Rehash(T)

$loadFactor \leftarrow \frac{T.numberOfKeys}{T.size}$

if $loadFactor > 0.9$:

 Create T_{new} of size $2 \times T.size$

 Choose h_{new} with cardinality $T_{new}.size$

 For each object in T :

 Insert object in T_{new} using h_{new}

$T \leftarrow T_{new}, h \leftarrow h_{new}$

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Rehash Running Time

You should call `Rehash` after each operation with the hash table

Similarly to dynamic arrays, single rehashing takes $O(n)$ time, but amortized running time of each operation with hash table is still $O(1)$ on average, because rehashing will be rare

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 $148-25-67 \rightarrow 1482567$
- As a result, any phone number will be converted to an integer less than 10^{15}
- If we come up with a **universal family** for integers up to 10^{15} , we will be able to map phone numbers to names efficiently using chaining

Hashing Integers

Lemma

$\mathcal{H}_p = \left\{ h_p^{a,b}(x) = ((ax + b) \bmod p) \bmod m \right\}$
for all $a, b : 1 \leq a \leq p - 1, 0 \leq b \leq p - 1$ is
a **universal family** for the set of integers
between 0 and $p - 1$, for any prime p .

Hashing Phone Numbers

Example

Select $a = 34$, $b = 2$, so $h = h_p^{34,2}$ and consider $x = 1\ 482\ 567$ corresponding to phone number 148-25-67. $p = 10\ 000\ 019$.

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Example

Select $a = 34$, $b = 2$, so $h = h_p^{34,2}$ and consider $x = 1\ 482\ 567$ corresponding to phone number 148-25-67. $p = 10\ 000\ 019$.

$$(34 \times 1482567 + 2) \bmod 10000019 = 407185$$

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$$407185 \bmod 1000 = 185$$

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$$407185 \bmod 1000 = 185$$

$$h(x) = 185$$

Proof Ideas

- For any pair of different keys (x, y) , any two of the $p(p - 1)$ hash functions in \mathcal{H}_p hash them into different pairs (r, s) of different remainders modulo p

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- For any pair of different keys (x, y) , any two of the $p(p - 1)$ hash functions in \mathcal{H}_p hash them into different pairs (r, s) of different remainders modulo p
- Thus any pair (r, s) of different remainders modulo p has equal probability $\frac{1}{p(p-1)}$
- The ratio of pairs (r, s) of different remainders modulo p such that $r \equiv s \pmod{m}$ is less than $\frac{1}{m}$ □

General Case

- Define maximum length L of a phone number

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- Choose random hash function from universal family \mathcal{H}_p (choose random $a \in [1, p - 1]$ and $b \in [0, p - 1]$)

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- You will learn how string hashing is implemented in Java!

String Length Notation

Definition

Denote by $|S|$ the length of string S .

Examples

$$|\text{"edx"}| = 3$$

$$|\text{"ucsd"}| = 4$$

$$|\text{"chaining"}| = 8$$

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- $S = S[0]S[1] \dots S[|S| - 1]$, where $S[i]$ are individual characters
- We should use all the characters in the hash function
- Otherwise there will be many collisions
- For example, if $S[0]$ is not used, then $h(\text{"aa"}) = h(\text{"ba"}) = \dots = h(\text{"za"})$

Preparation

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Polynomial Hashing

Definition

Family of hash functions

$$\mathcal{P}_p = \left\{ h_p^x(S) = \sum_{i=0}^{|S|-1} S[i]x^i \bmod p \right\}$$

with a fixed prime p and all $1 \leq x \leq p - 1$ is called **polynomial**.

PolyHash(S, p, x)

hash $\leftarrow 0$

for i from $|S| - 1$ down to 0:

 hash $\leftarrow (\text{hash} \cdot x + S[i]) \bmod p$

return hash

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Example: $|S| = 3$

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2 hash $\leftarrow S[2] \bmod p$

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3 hash $\leftarrow S[1] + S[2]x \bmod p$

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Example: $|S| = 3$

1 hash $\leftarrow 0$

2 hash $\leftarrow S[2] \bmod p$

3 hash $\leftarrow S[1] + S[2]x \bmod p$

4 hash $\leftarrow S[0] + S[1]x + S[2]x^2 \bmod p$

Java Implementation

The method `hashCode` of the built-in Java class `String` is very similar to our `PolyHash`, it just uses $x = 31$ and for technical reasons avoids the $(\text{mod } p)$ operator.

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You now know the implementation of the function that is used trillions of times a day in many thousands of programs!

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Lemma

For any two different strings s_1 and s_2 of length at most $L + 1$, if you choose h from \mathcal{P}_p at random (by selecting a random $x \in [1, p - 1]$), the probability of collision $\Pr[h(s_1) = h(s_2)]$ is at most $\frac{L}{p}$.

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Proof idea

This follows from the fact that the equation $a_0 + a_1x + a_2x^2 + \dots + a_Lx^L = 0 \pmod{p}$ for prime p has at most L different solutions x .

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Cardinality Fix

For use in a hash table of size m , we need a hash function of cardinality m .

First, apply random h_x from \mathcal{P}_p , and then hash the resulting value again using universal family for integers. Denote the resulting function by h_m .

$$h_m(S) = h_{a,b}(h_x(S)) \bmod m$$

Lemma

For any two different strings s_1 and s_2 of length at most $L + 1$ and cardinality m , the probability of collision $\Pr[h_m(s_1) = h_m(s_2)]$ is at most $\frac{1}{m} + \frac{L}{p}$.

Polynomial Hashing

Corollary

If $p > mL$, for any two different strings s_1 and s_2 of length at most $L + 1$ the probability of collision $\Pr[h_m(s_1) = h_m(s_2)]$ is $O(\frac{1}{m})$.

Proof

$$\frac{1}{m} + \frac{L}{p} < \frac{1}{m} + \frac{L}{mL} = \frac{1}{m} + \frac{1}{m} = \frac{2}{m} = O\left(\frac{1}{m}\right) \quad \square$$

Running Time

- For $p > mL$ we have

$$c = O\left(1 + \frac{n}{m}\right) = O(1 + \alpha) \text{ again}$$

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- Computing $\text{PolyHash}(S)$ runs in $O(|S|)$
- If lengths of the names in the phone book are bounded by constant L , computing $h(S)$ takes $O(L) = O(1)$ time

Conclusion

- You learned how to hash integers and strings
- Phone book can be implemented as two hash tables
- Mapping phone numbers to names and back
- Search and modification run in $O(1)$ on average!