the best data structure!

Data Structures and Algorithms

Hashing

CS 225
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November 12, 2025

when in doubt, use a hash!

:)

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Randomization in Algorithms

→ Brad's take

1. Assume input data is random to estimate average-case performance

↳ BST is more likely log n height (weak)

2. Use randomness inside algorithm to estimate expected running time

↳ 100% correct

↳ Randomized quicksort

↳ selection of pivot ← randomness is on runtime

3. Use randomness inside algorithm to approximate solution in fixed time

O(1)

↳ Fermat's primality test

↳ selection of some constant

↑ randomness is correctness

Learning Objectives

Motivate and formally define a hash table

Discuss what a 'good' hash function looks like

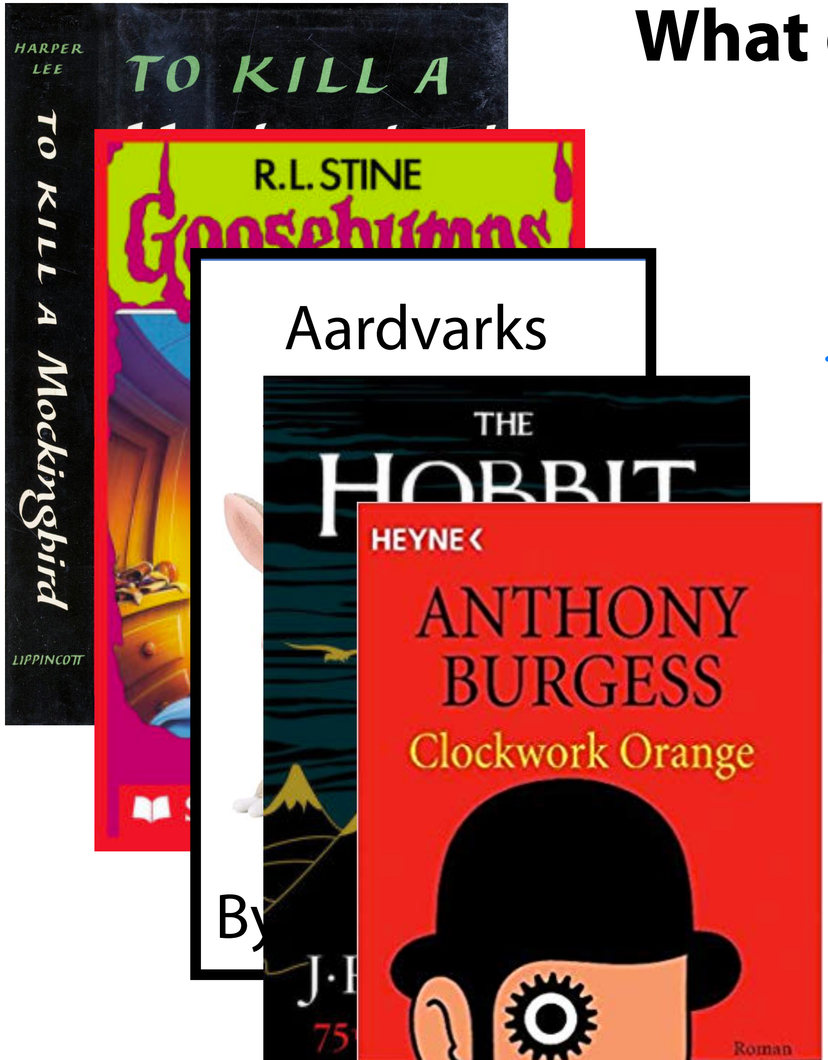
Identify the key weakness of a hash table

Introduce strategies to "correct" this weakness

Data Structure Review

Keys: Title
Value: contents

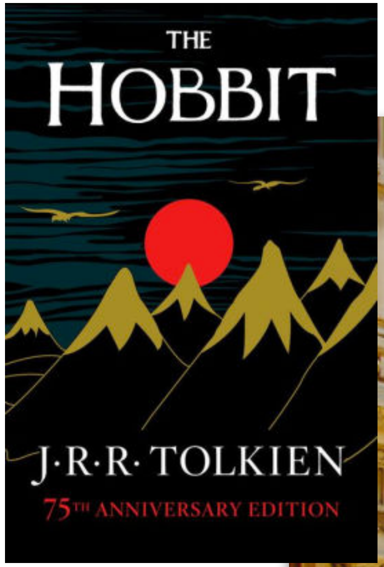
I have a collection of books and I want to store them in a dictionary!

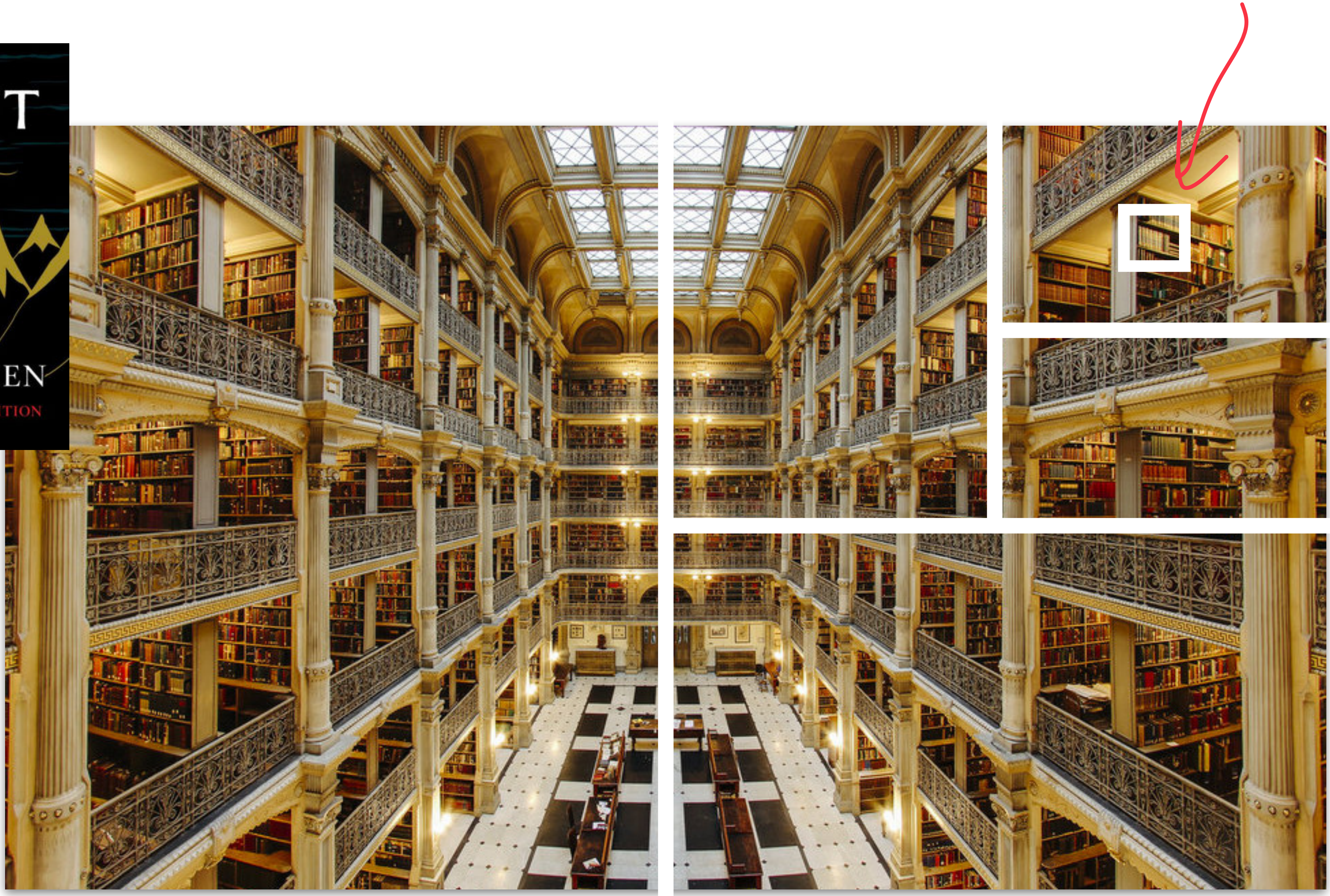


What data structures can I use here?

	BST	AVL Tree	min-heap
Insert	$O(h) = O(n)$	$O(h) = O(\log n)$	$O(1)$ / $O(n)$
Remove	$O(h) = O(n)$	$O(\log n)$	
Find	$O(h) = O(n)$	$O(\log n)$	

What if $O(log\ n)$ isn't good enough?





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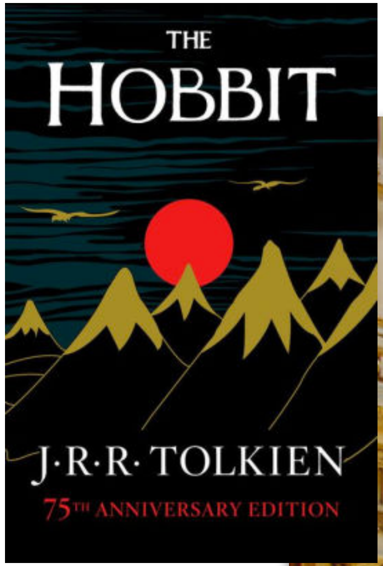
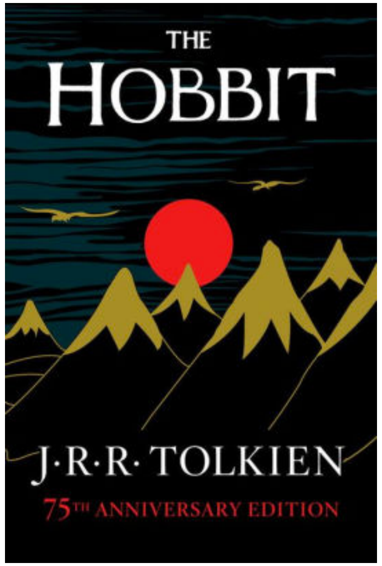


O(1) address lookup

O(1) lookup address

A Hash Table based Dictionary

Some arb input



(Key)

A number / an address

ISBN: 9780062265722

Call #: PR
6068.O93
H35 1937

Address

ISBN: 9780062265722

Call #: PR
6068.O93
H35 1937

look up

(Value)

Chapter I

AN UNEXPECTED PARTY

In a hole in the ground there lived a hobbit. Not a nasty, dirty, wet hole, filled with the ends of worms and an oozy smell, nor yet a dry, bare, sandy hole with nothing in it to sit down on or to eat: it was a hobbit-hole, and that means comfort.

It had a perfectly round door like a porthole, painted green, with a shiny yellow brass knob in the exact middle. The door opened on to a tube-shaped hall like a tunnel: a very comfortable tunnel without smoke, with panelled walls, and floors tiled and carpeted, provided with polished chairs, and lots and lots of pegs for hats and coats—the hobbit was fond of visitors. The tunnel wound on and on, going fairly but not quite straight into the side of the hill—The Hill, as all the people for many miles round called it—and many little round doors opened out of it, first on one side and then on another. No going upstairs for the hobbit: bedrooms, bathrooms, cellars, pantries (lots of these), wardrobes (he had whole rooms devoted to clothes), kitchens, dining-rooms, all were on the same floor, and indeed on the same passage. The best rooms were all on the left-hand side (going in), for these were the only ones to have windows, deep-set round windows looking over his garden, and meadows beyond, sloping down to the river.

This hobbit was a very well-to-do hobbit, and his name

1

Randomized Data Structures

Sometimes a data structure can be **too ordered / too structured**

↳ Tradeoff arg! Benefit of sorting data is O(log n) search

Downside O(log n) insert

Randomized data structures rely on **expected** performance

Randomized data structures 'cheat' tradeoffs!

A Hash Table based Dictionary

User Code (is a map):

```
Dictionary<KeyType, ValueType> d;
d[k] = v;
```

A **Hash Table** consists of three things:

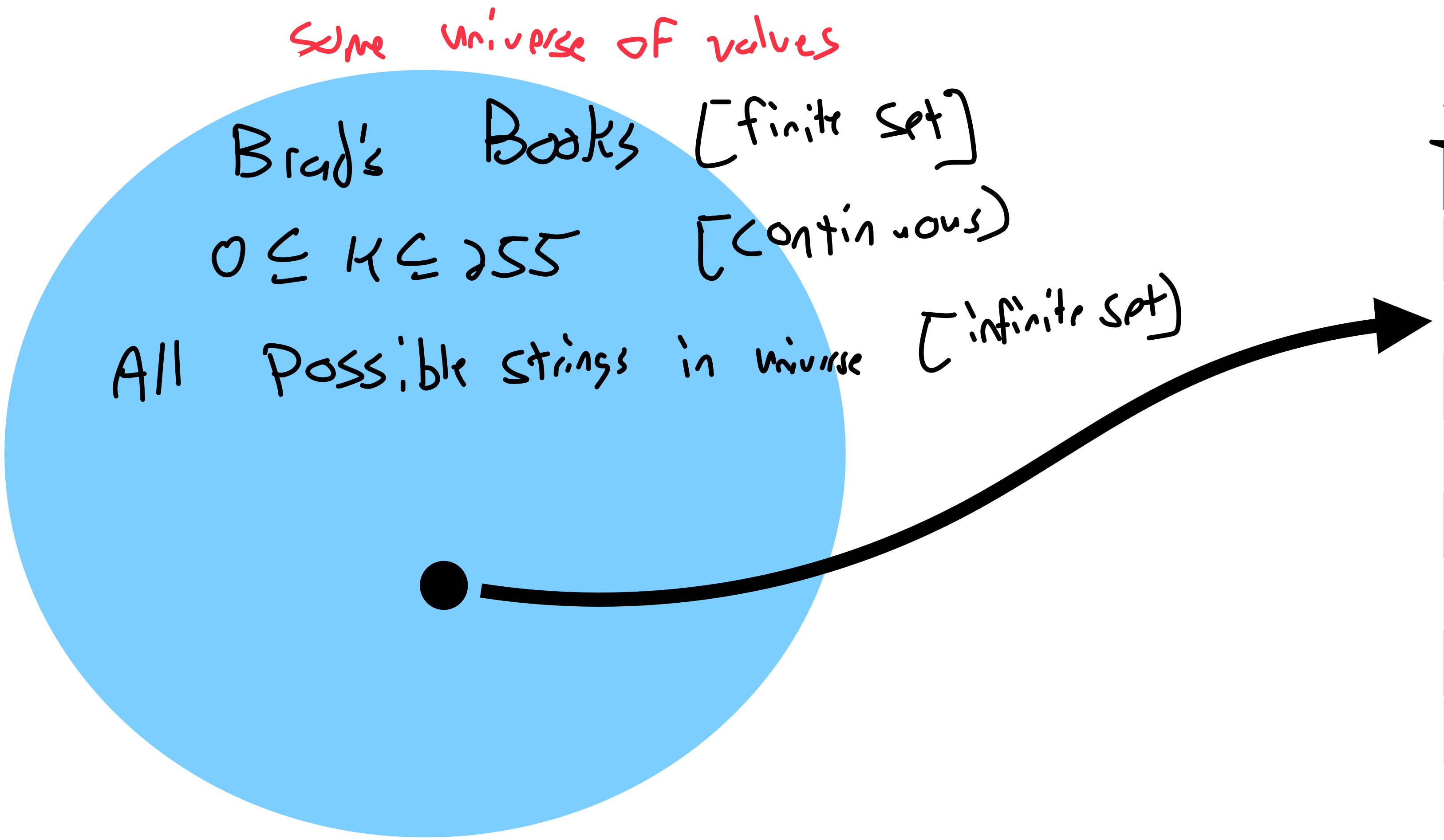
1. A hash function (key input → A number/address output)

2. A data storage structure (A List!)

3. ?? Something to handle 'chaos'

Hash Function

Maps a **keyspace**, a (mathematical) description of the keys for a set of data, to a set of integers.



List

***m* elements**

Key	Value

Hash Function

A hash function ***must*** be:

- **Deterministic:** If you input same key twice, get same output
- **Efficient:** $O(1)$ is goal
- **Defined for a certain size table:** $h(k) \rightarrow [0 \dots m-1]$

  ↑ we have list of size m

Hash Function

(Angrave, CS 241)
(Beckman, CS 421)
(Challon, CS 125)
(Davis, CS 101)
(Evans, CS 225)
(Fagen-Ulmschneider, CS 107)
(Gunter, CS 422)
(Herman, CS 233)

Hash function

$h(k) = k[0] - \text{'A'}$

e.g. get 0th letter
A = 0
B = 1
C = 2
⋮

Key	Value
Angrave	241
Beckman	421

Hash Function

Problem 1: Collisions

If this is my only dataset, this is a perfect hash

(Angrave, CS 241)   Alawini 411

(Beckman, CS 421)

(Challon, CS 125)

(Davis, CS 101)

(Evans, CS 225)

(Fagen-Ulmschneider, CS 107)

(Gunter, CS 422)

(Herman, CS 233)

Soloman 225

Hash function

(key[0] - 'A')

collision!

Key	Value
Angrave	241
Beckman	421
Challon	125
Davis	101
Evans	225
Fagen-U	107
Gunter	422
Herman	233

S?? →

Problem 2: Not mapped to [0, m-1]

General Hash Function

An $O(1)$ deterministic operation that maps all keys in a universe U to a defined range of integers $[0, \ldots, m-1]$

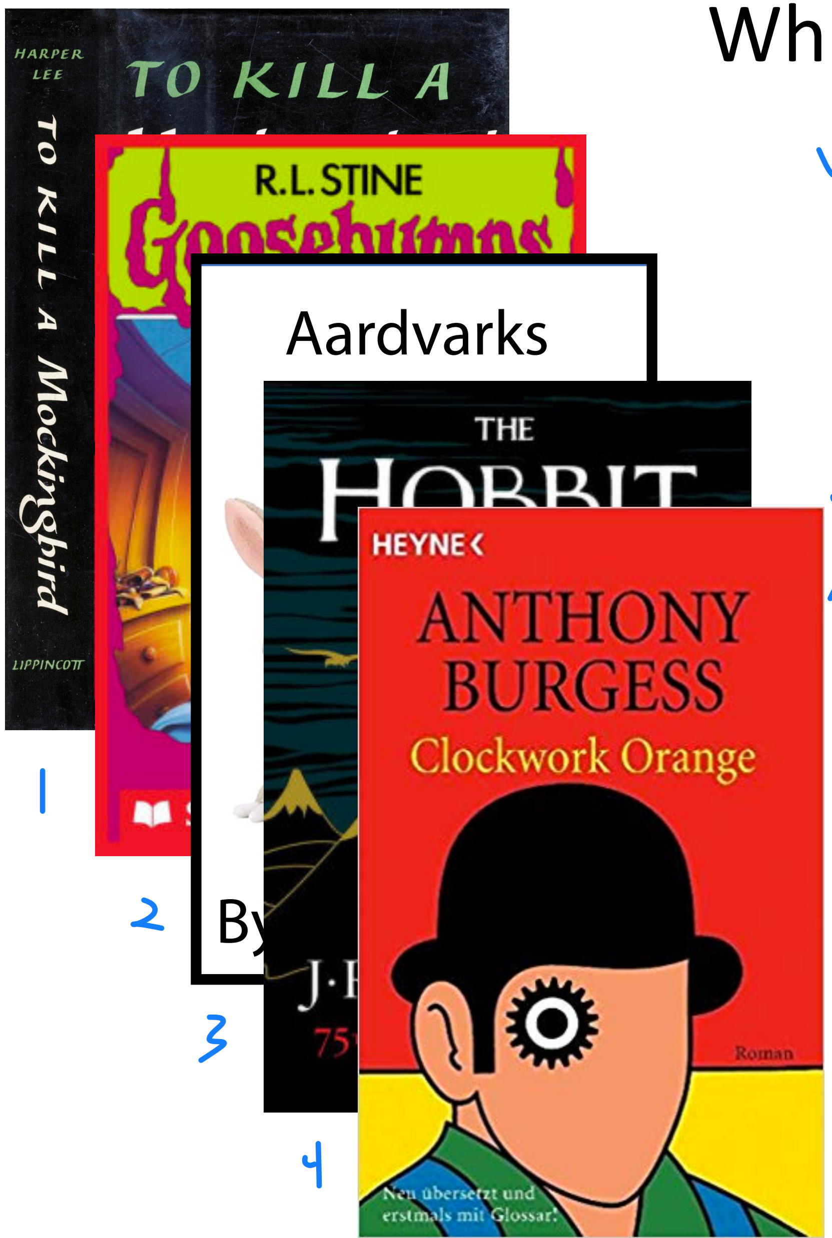
- A **hash**:

- A **compression**:

Choosing a good hash function is tricky…

- Don't create your own (yet*)

Hash Function



0
1
2
3
4

Which of the following are valid hashes?

✓ first and last name first character

$$h_1(k) = (k.firstName[0] + k.lastName[0])\ \%\ m$$

↳ Deterministic ↳ O(1) ↳ fixed range

↳ Can have collisions

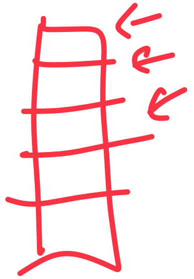
✗ Generate random # multiply by page count

$$h_2(k) = (rand() * k.numPages)\ \%\ m$$

10%

↳ Not deterministic

Insert Book



✗

$$h_3(k) = (\text{Order I insert [Order seen]})\ \%\ m$$

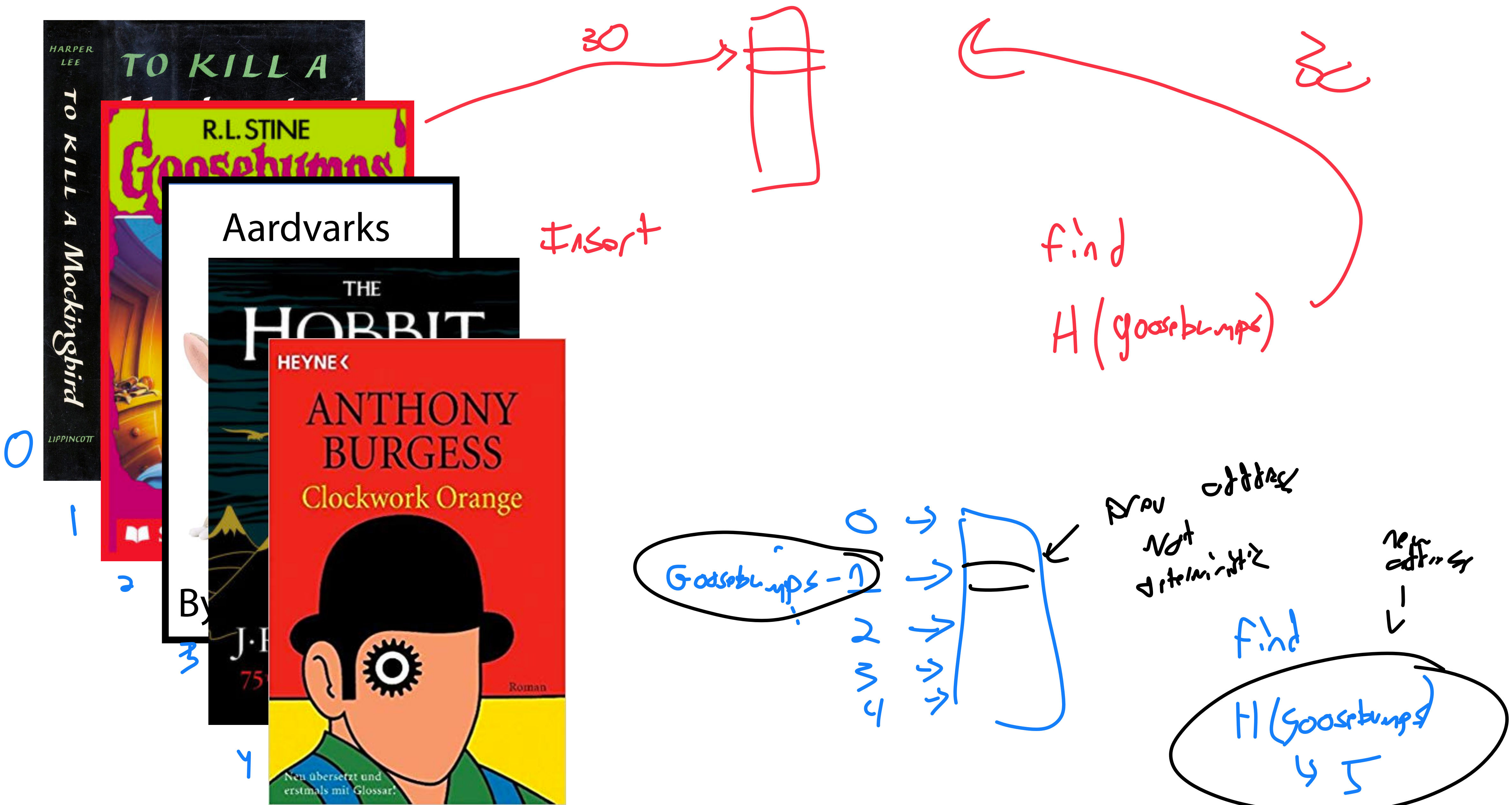
30%

↳ Not deterministic

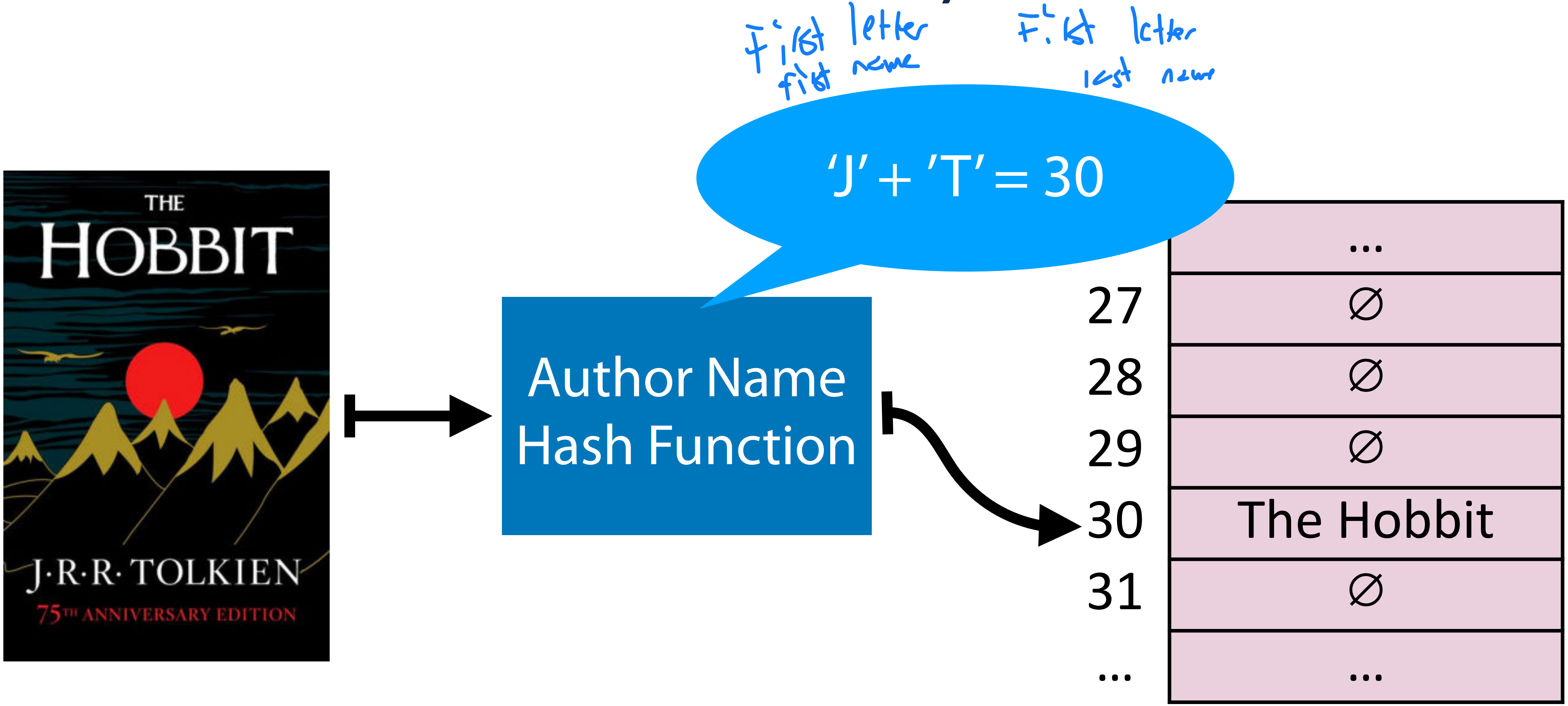
No way of converting query to an previous address

5th

Hash Function



A Hash Table based Dictionary



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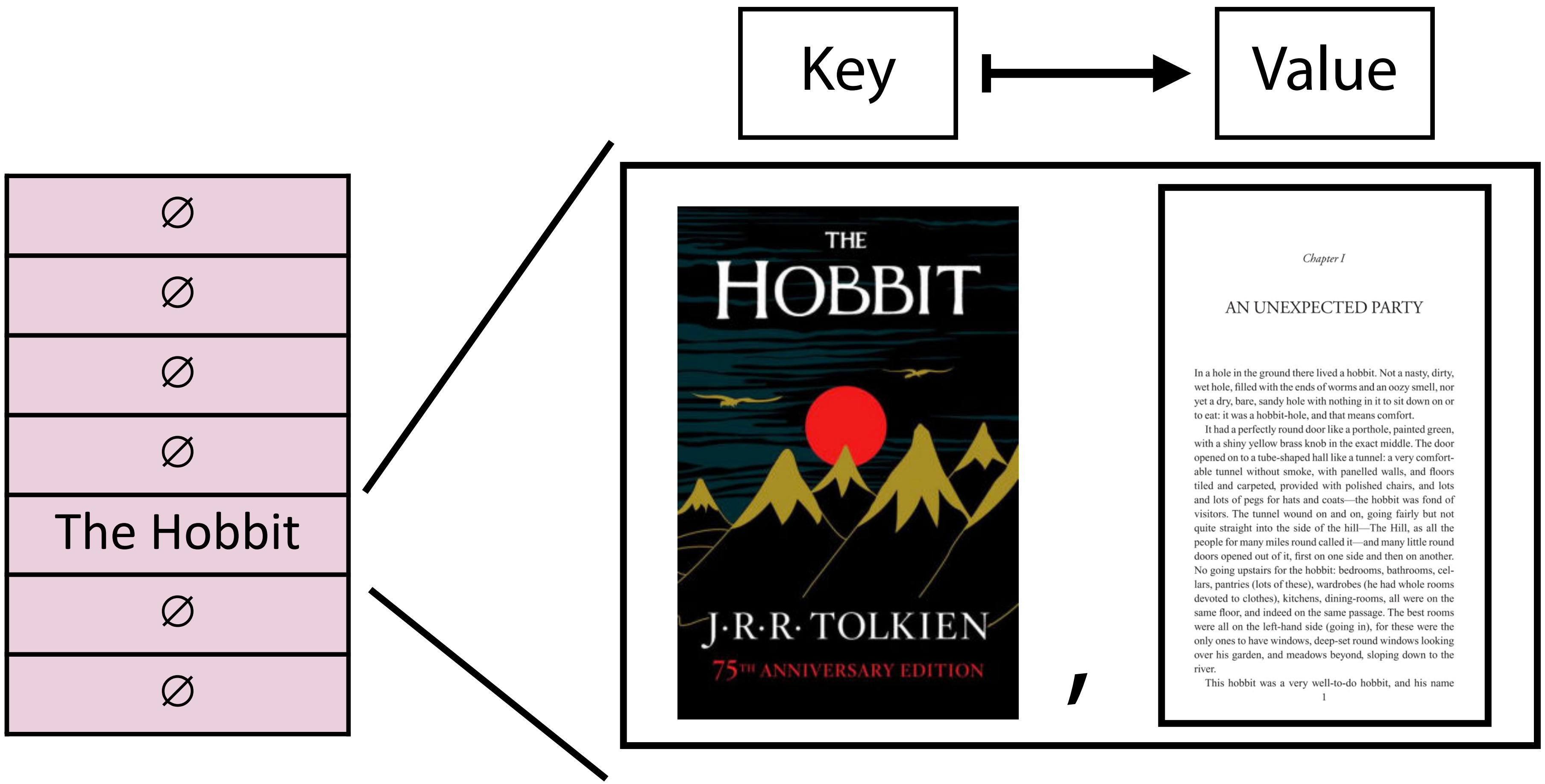
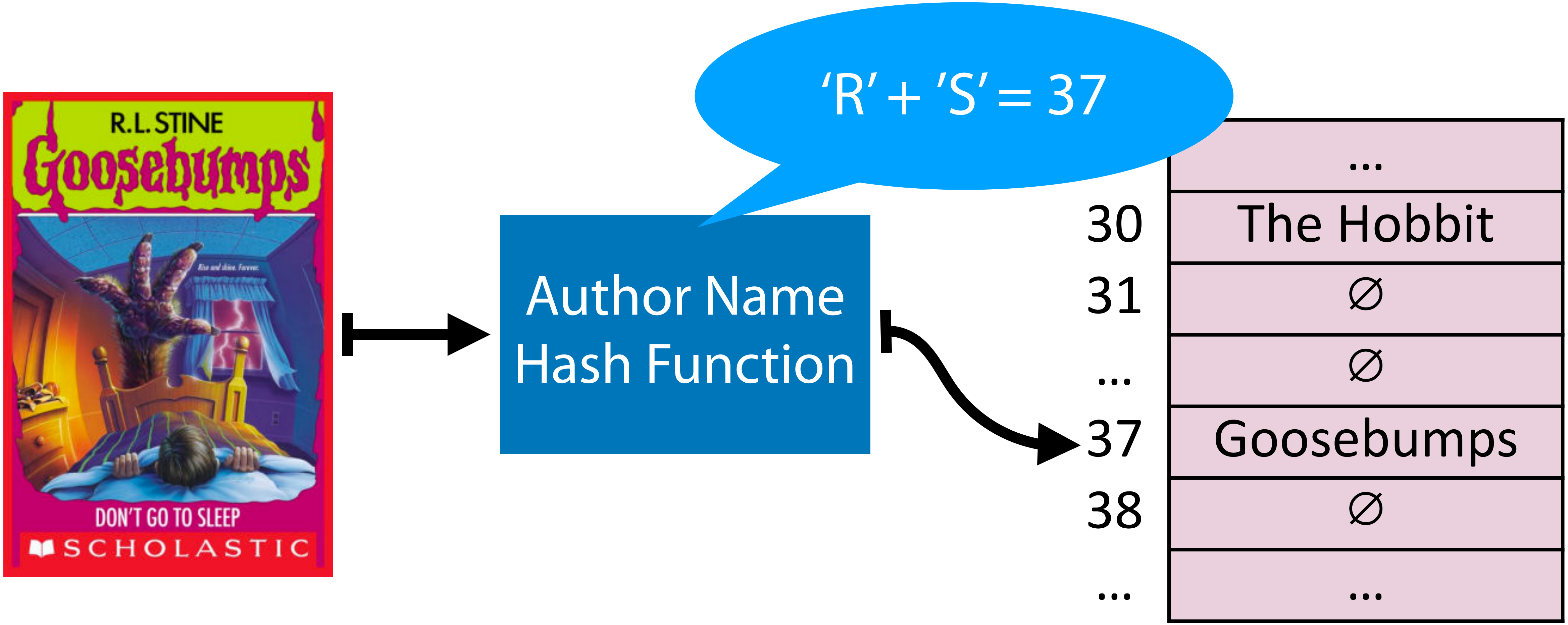
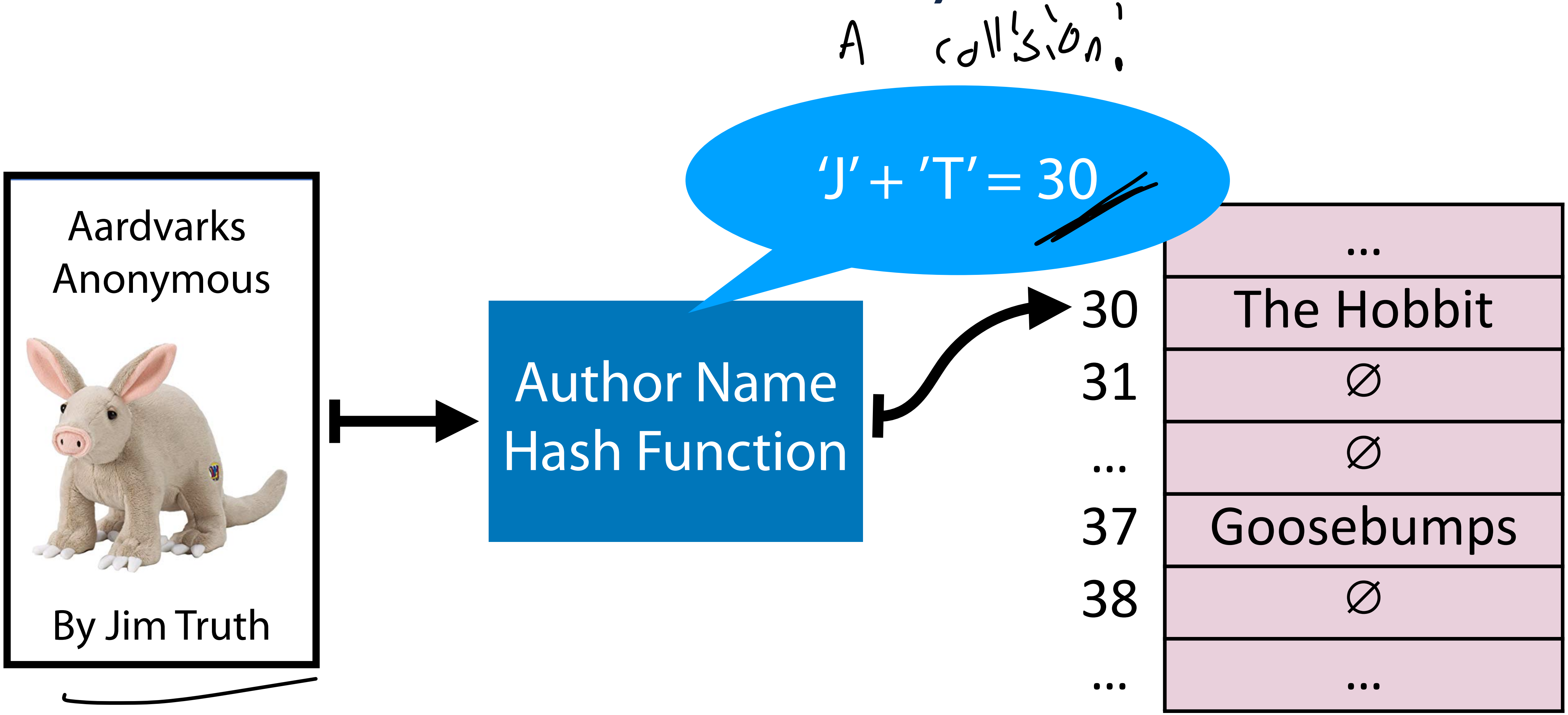


A Hash Table based Dictionary

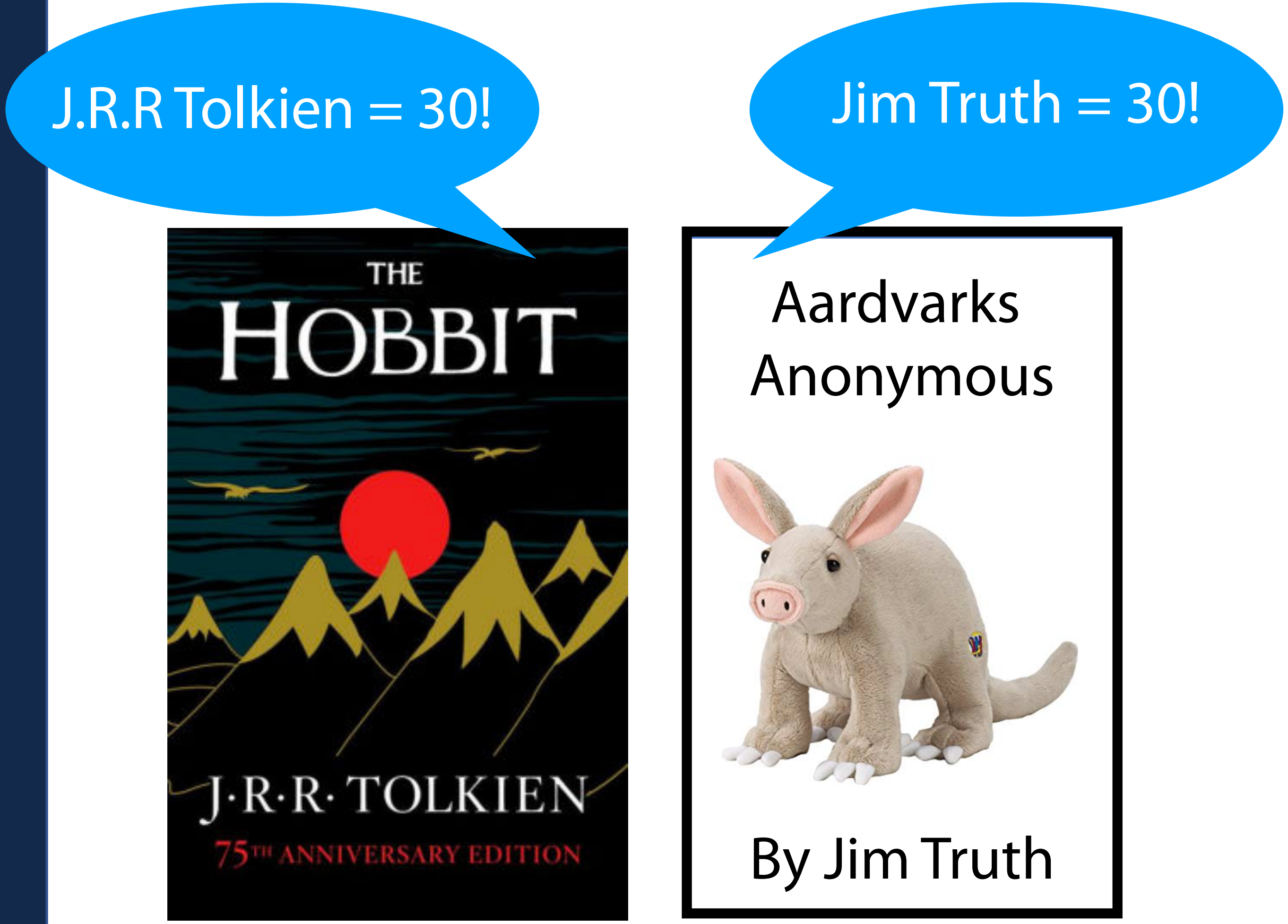


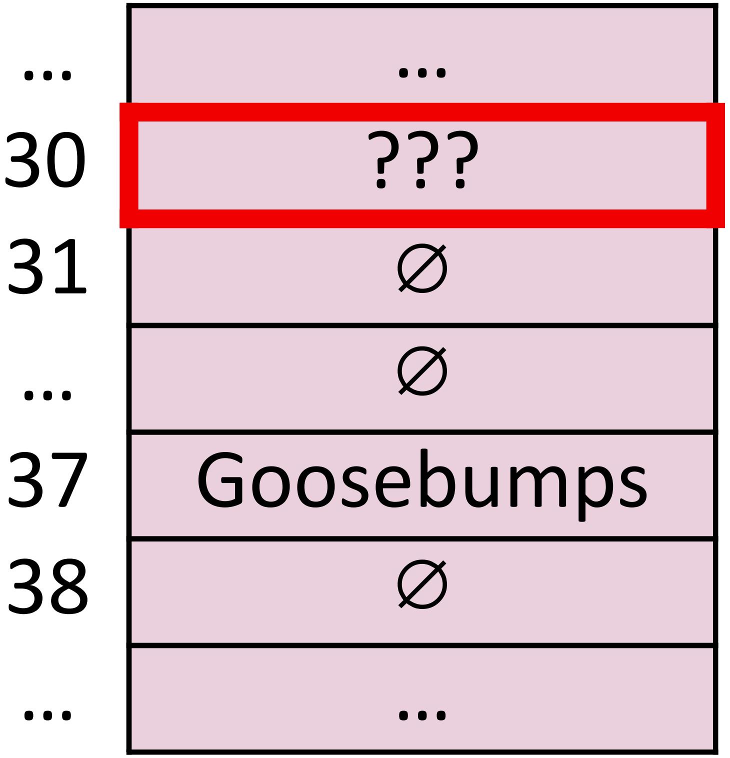
A Hash Table based Dictionary



Hash Collision

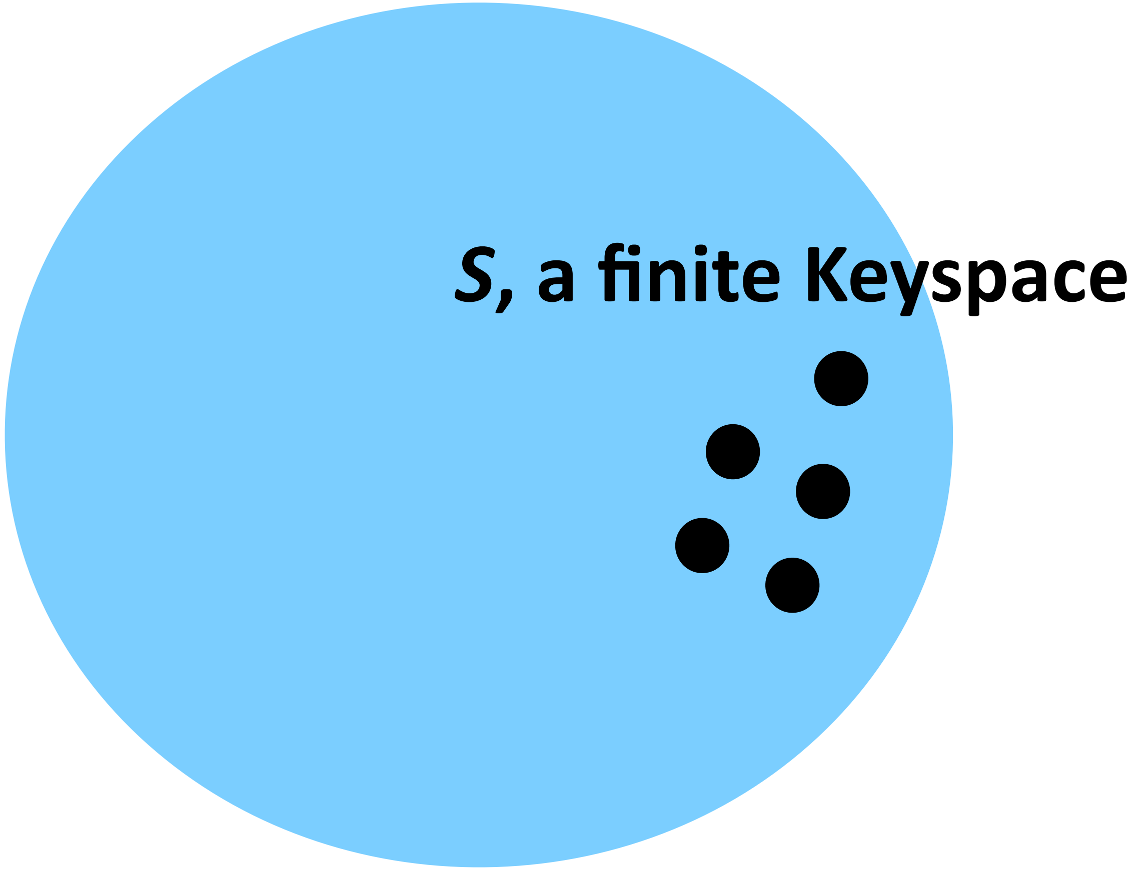
A ***hash collision*** occurs when multiple unique keys hash to the same value





Perfect Hashing

If $m \geq S$, we can write a *perfect* hash with no collisions

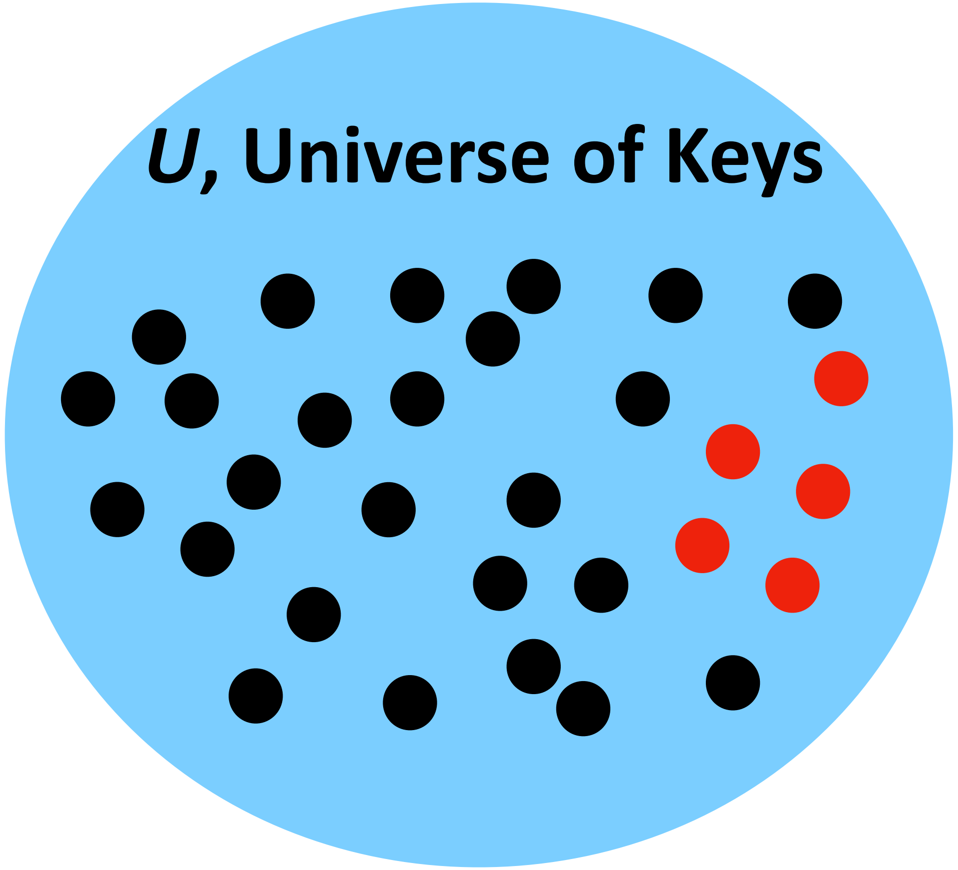


***m* elements**

Key	Value

General Purpose Hashing

In CS 225, we want our hash functions to work *in general*.

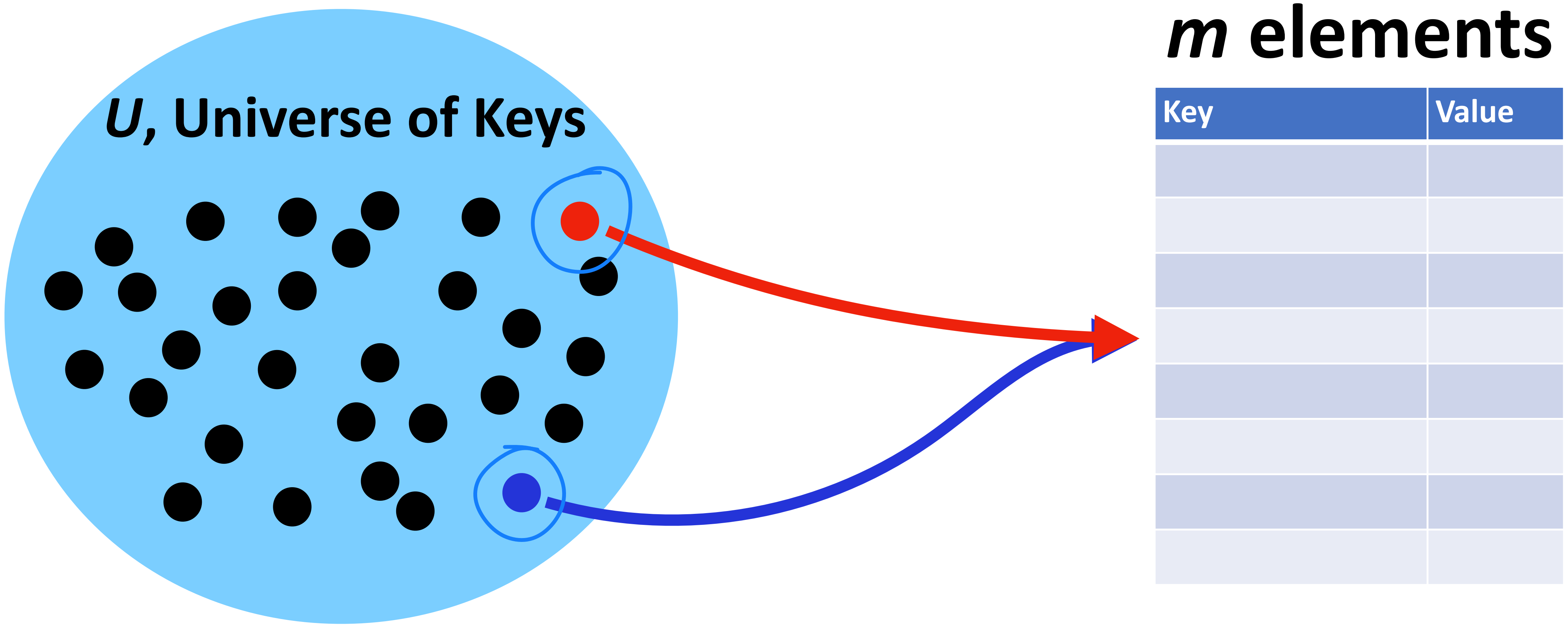


***m* elements**

Key	Value

General Purpose Hashing

If $m < U$, there must be at least one hash collision.



General Purpose Hashing

By fixing h, we open ourselves up to adversarial attacks.

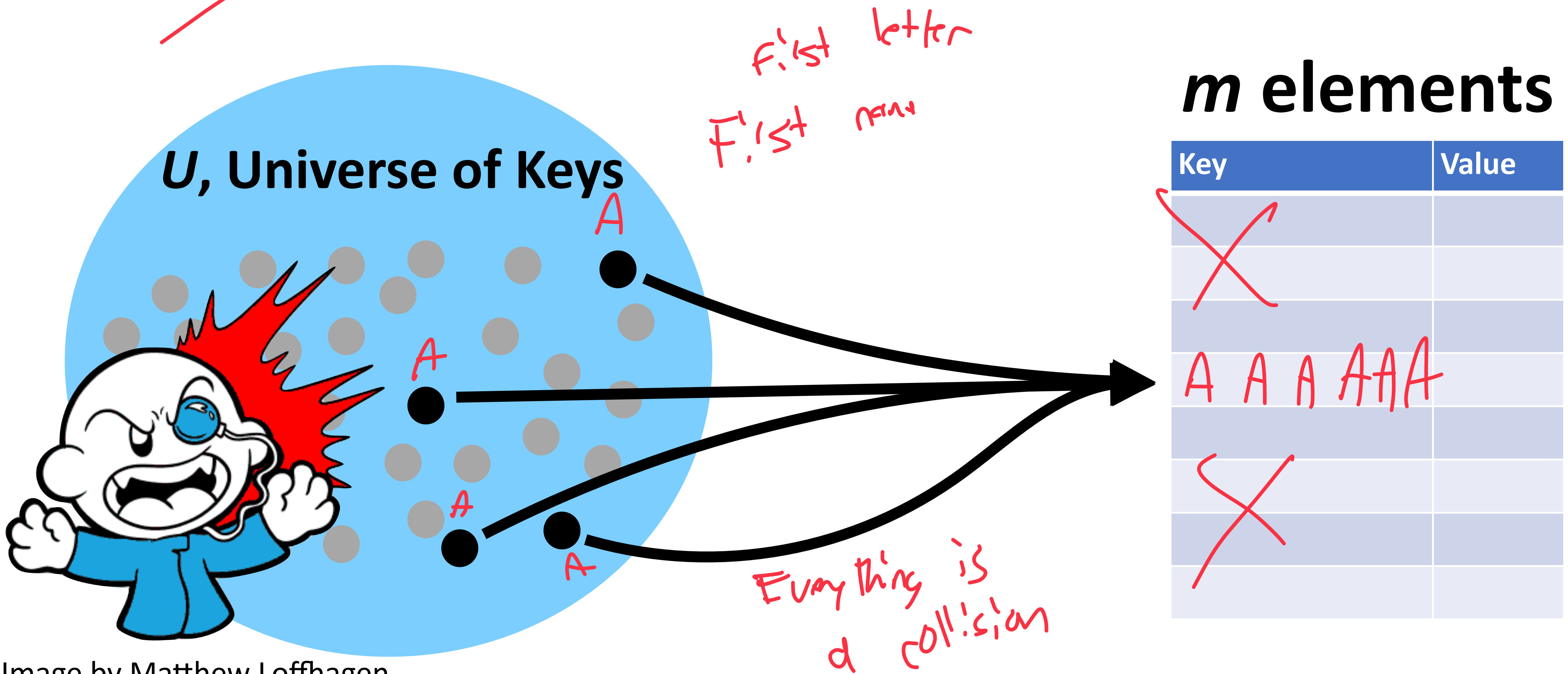


Image by Matthew Loffhagen

A Hash Table based Dictionary

User Code (is a map):

```
Dictionary<KeyType, ValueType> d;
d[k] = v;
```

A **Hash Table** consists of three things:

1. A hash function

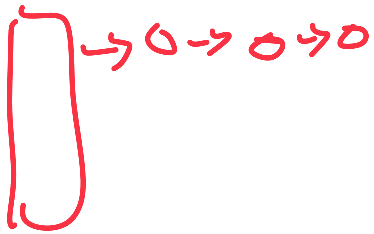
2. A data storage structure

3. A method of addressing *hash collisions*

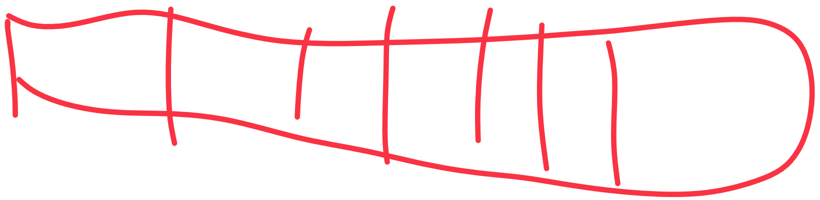
Open vs Closed Hashing

Addressing hash collisions depends on your storage structure.

- **Open Hashing:** Store K, V in some external data structure

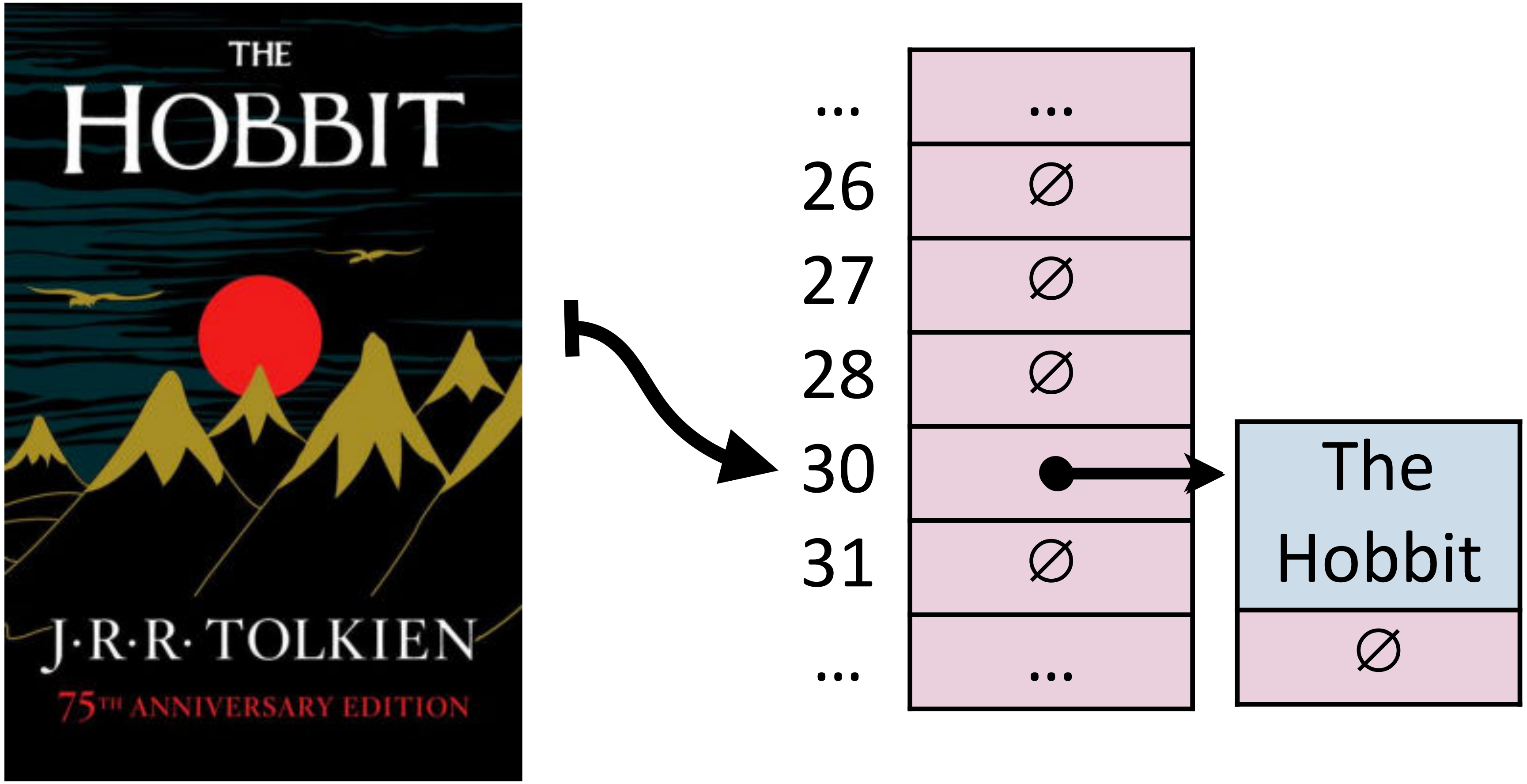


- **Closed Hashing:** Store K,V in one fixed size array



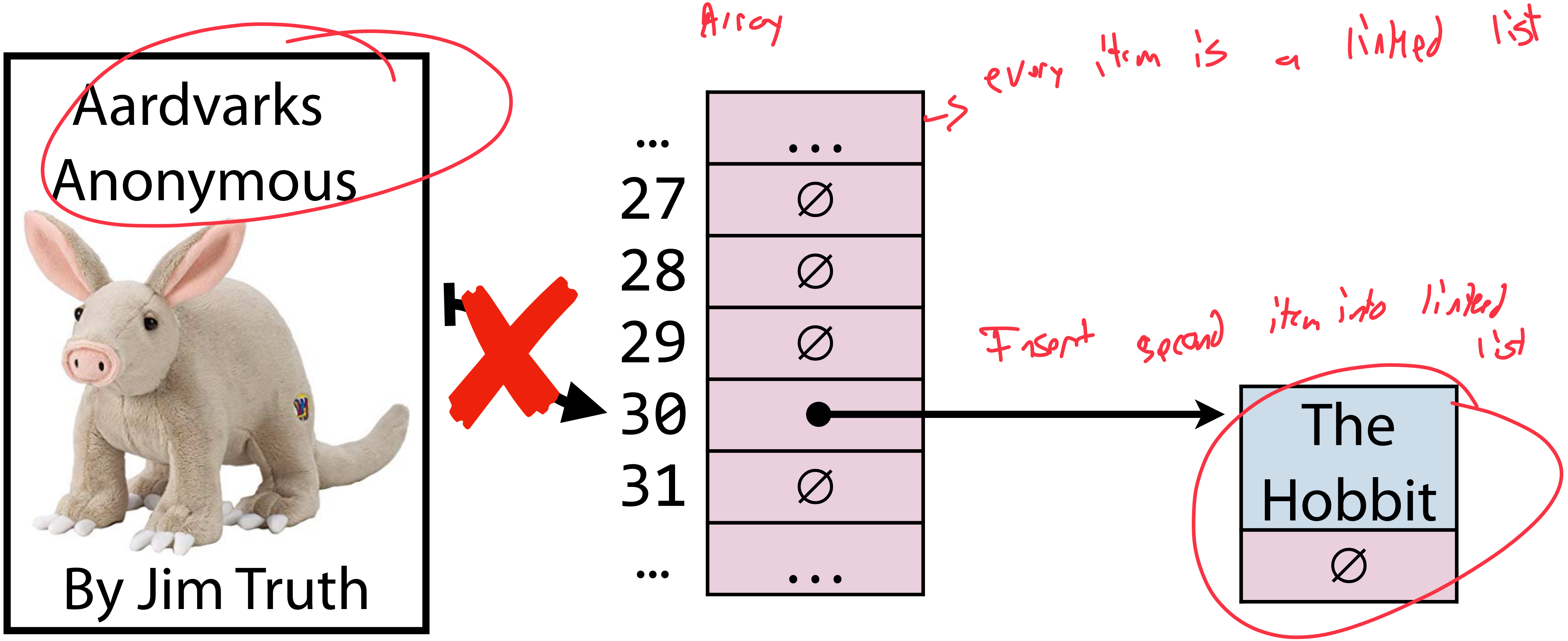
Open Hashing

In an ***open hashing*** scheme, key-value pairs are stored externally (for example as a linked list).



Hash Collisions (Open Hashing)

A ***hash collision*** in an open hashing scheme can be resolved by _extend the chain_________________. This is called ***separate chaining*.**

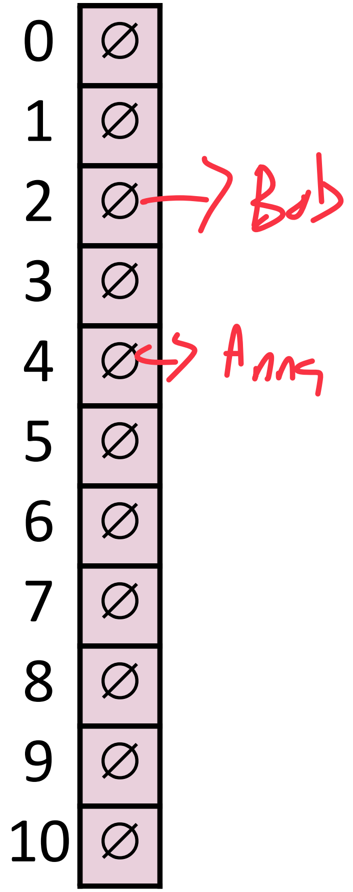


Insertion (Separate Chaining)

```
_insert("Bob")

_insert("Anna")
```

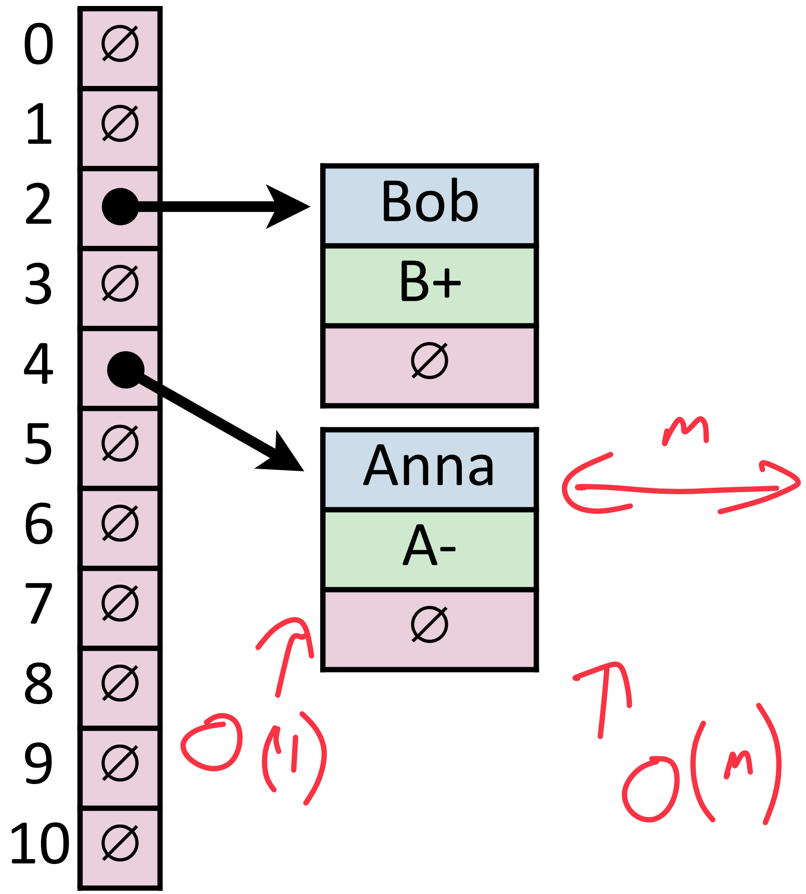
Key	Value	Hash
Bob	**B+**	**2**
Anna	**A-**	**4**
Alice	A+	4
Betty	B	2
Brett	A-	2
Greg	A	0
Sue	B	7
Ali	B+	4
Laura	A	7
Lily	B+	7



Insertion (Separate Chaining) `_insert("Alice")`

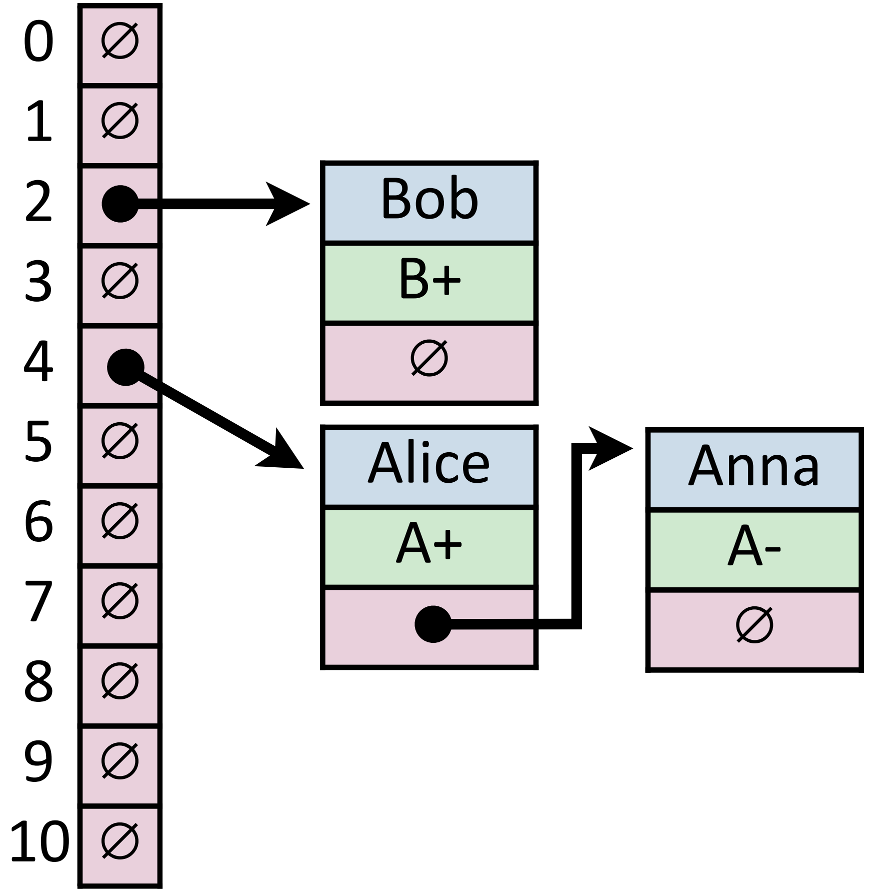
Where does Alice end up in the hash table?

Key	Value	Hash
Bob	B+	2
Anna	A-	4
Alice	**A+**	**4**
Betty	B	2
Brett	A-	2
Greg	A	0
Sue	B	7
Ali	B+	4
Laura	A	7
Lily	B+	7



Insertion (Separate Chaining)

Key	Value	Hash
Bob	B+	2
Anna	A-	4
Alice	A+	4
Betty	**B**	**2**
Brett	A-	2
Greg	A	0
Sue	B	7
Ali	B+	4
Laura	A	7
Lily	B+	7



Insertion (Separate Chaining)

Key	Value	Hash
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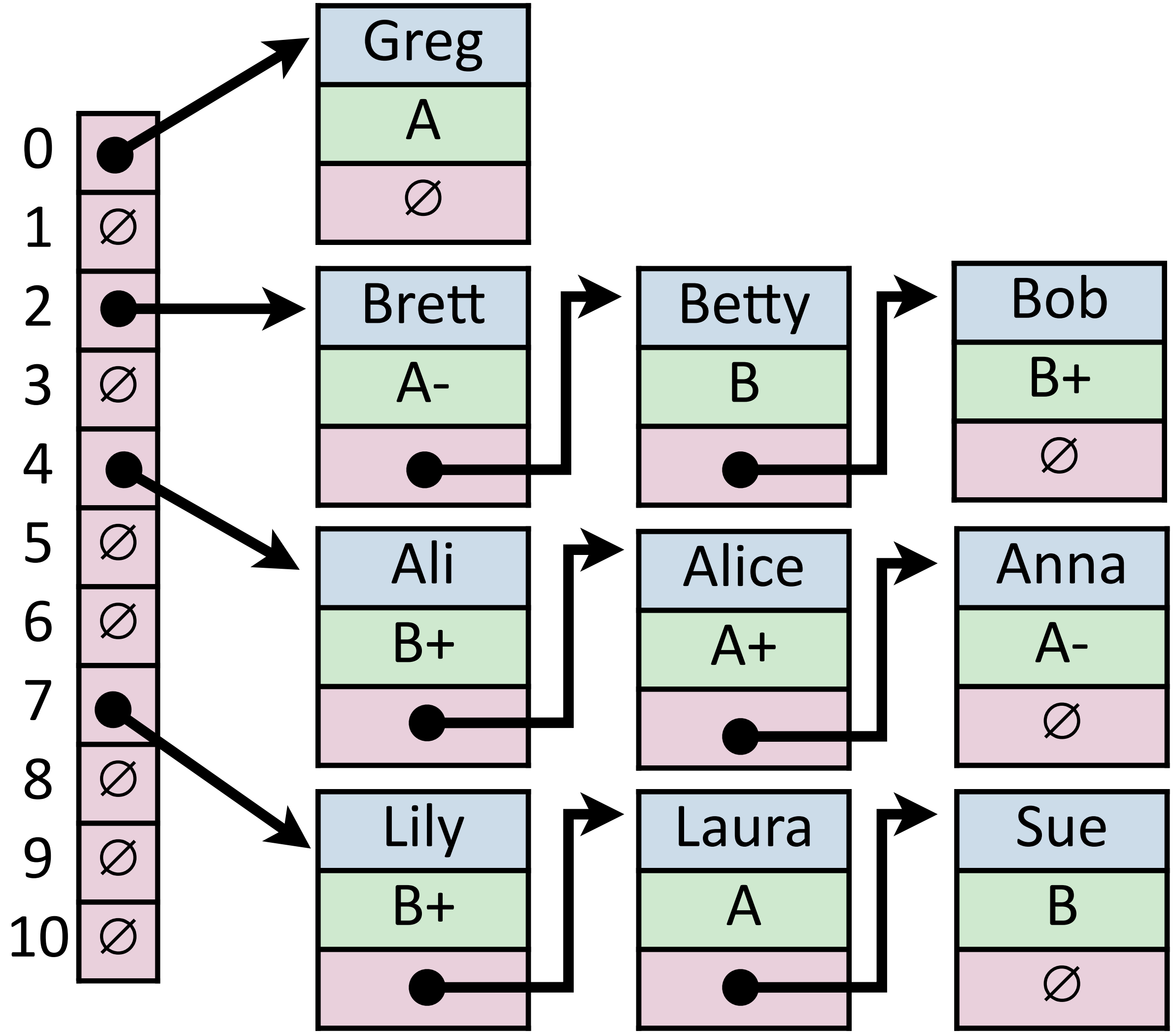
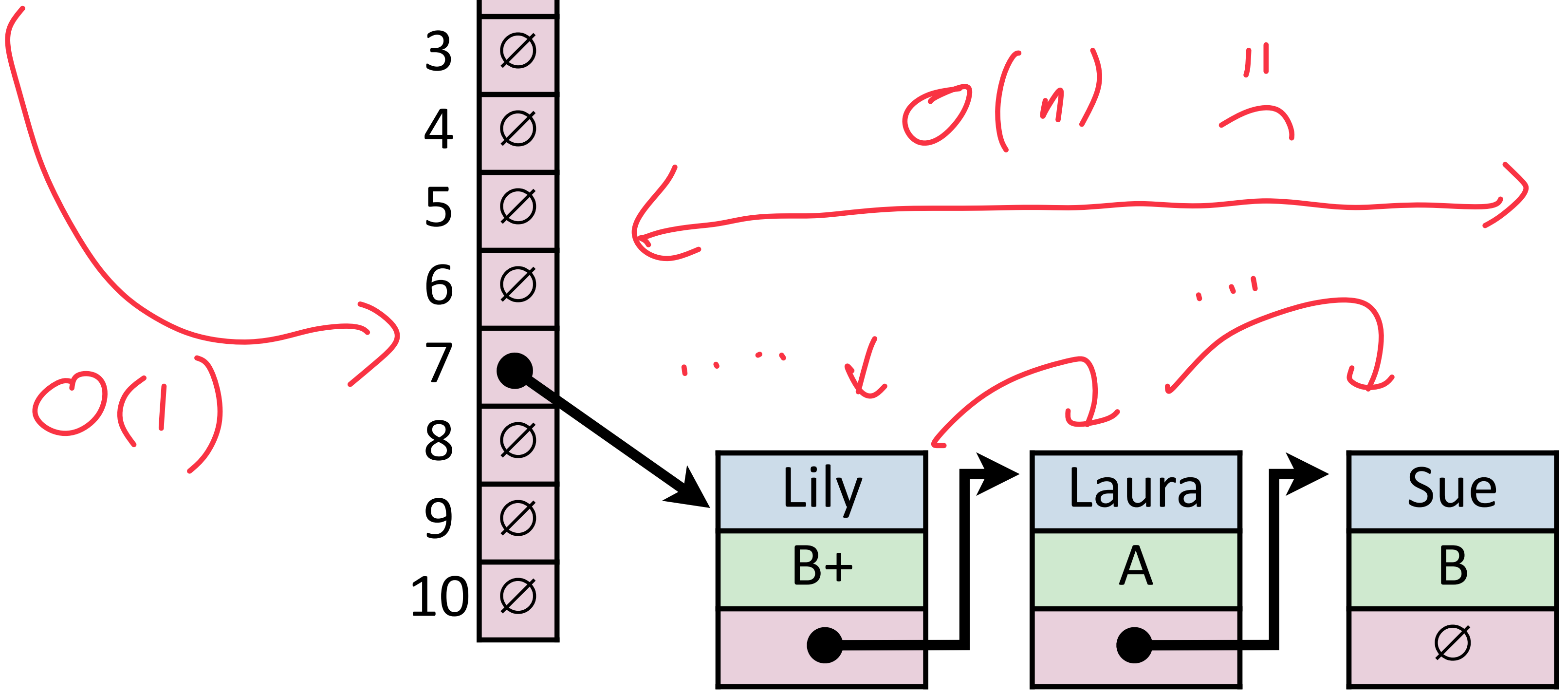
Lily	B+	7



Find (Separate Chaining)

`_find("Sue")`

Key	Hash
Sue	7

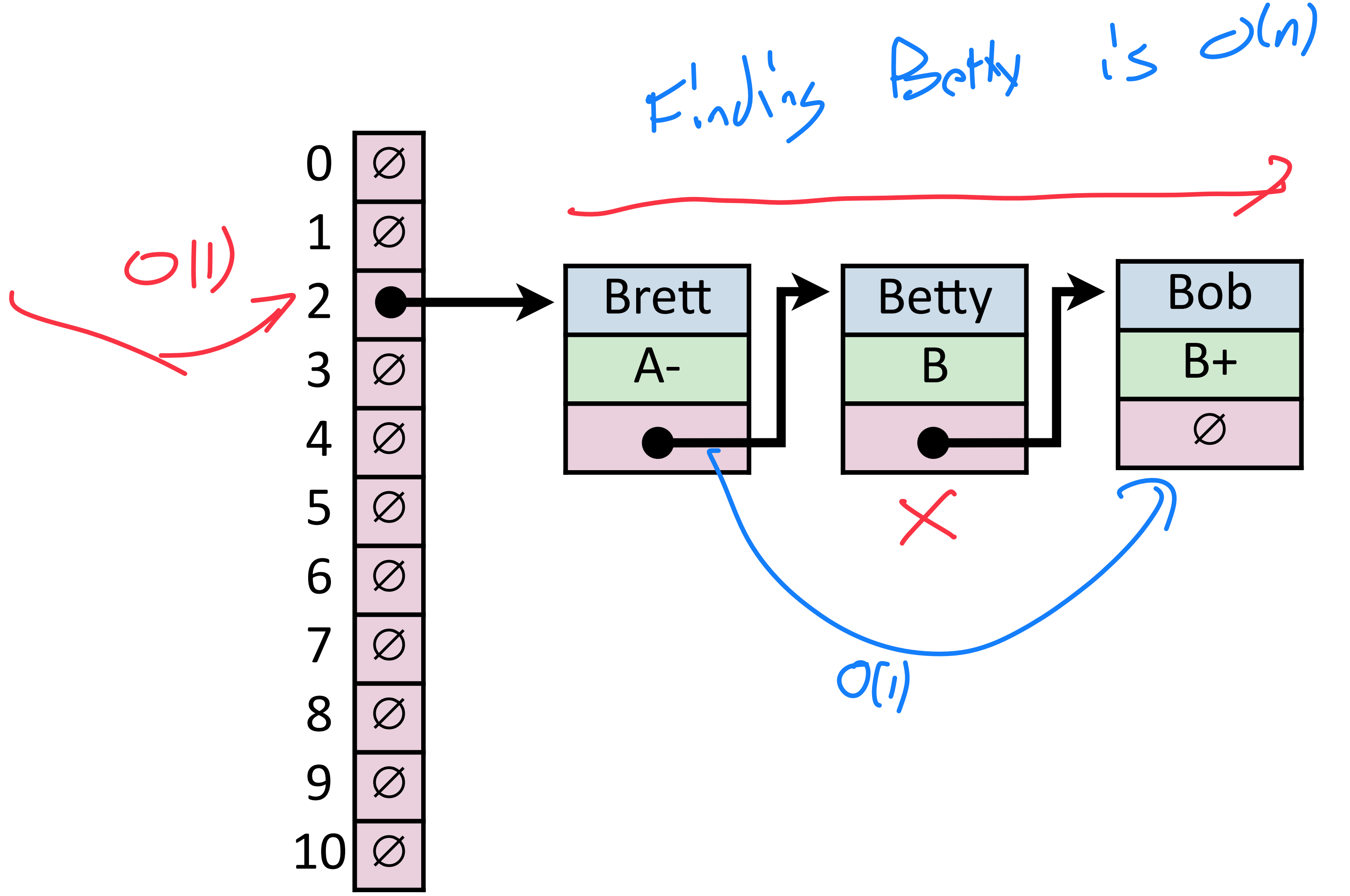


Remove (Separate Chaining)

`_remove("Betty")`

O(1)

Key	Hash
Betty	2



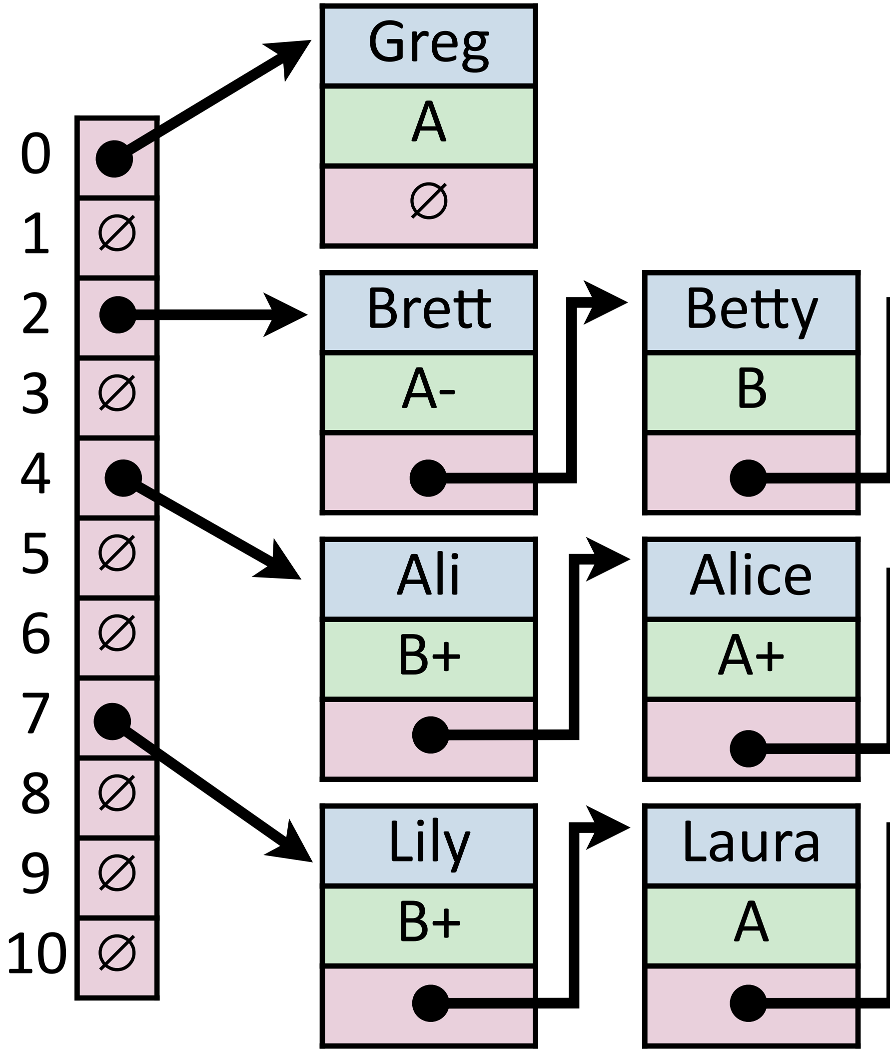
Hash Table (Separate Chaining)

For hash table of size *m* and *n* elements:

Find runs in: O(n) ______________

Insert runs in: O(1) ______________

Remove runs in: O(n) ______________



Hash Table

Worst-Case behavior is bad — but what about randomness?

1) **Fix *h***, our hash, and assume it is good for ***all keys***:

2) Create a ***universal hash function family:***

Simple Uniform Hashing Assumption

Given table of size m, a simple uniform hash, h, implies

$$\forall k_1, k_2 \in U \text{ where } k_1 \neq k_2, \; Pr(h[k_1] = h[k_2]) = \frac{1}{m}$$

Uniform:

Independent:

Separate Chaining Under SUHA

Table Size: m

Num objects: n

Claim: Under SUHA, expected length of chain is $\frac{n}{m}$

$\alpha_j =$ expected # of items hashing to position j

$$\alpha_j = \sum_i H_{i,j}$$

$$H_{i,j} = \begin{cases} 1 \text{ if item i hashes to j} \\ 0 \text{ otherwise} \end{cases}$$

Separate Chaining Under SUHA

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Claim: Under SUHA, expected length of chain is $\frac{n}{m}$

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$$\alpha_j = \sum_i H_{i,j}$$

$$H_{i,j} = \begin{cases} 1 \text{ if item i hashes to j} \\ 0 \text{ otherwise} \end{cases}$$

$$E[\alpha_j] = E[\sum_i H_{i,j}]$$

Separate Chaining Under SUHA

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$$\alpha_j = \sum_i H_{i,j}$$

$$H_{i,j} = \begin{cases} 1 \text{ if item i hashes to j} \\ 0 \text{ otherwise} \end{cases}$$

$$E[\alpha_j] = E\left[\sum_i H_{i,j}\right]$$

$$E[\alpha_j] = \sum_i Pr(H_{i,j} = 1) * 1 + Pr(H_{i,j} = 0) * 0$$

Separate Chaining Under SUHA

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Num objects: n

Claim: Under SUHA, expected length of chain is $\frac{n}{m}$

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$$\alpha_j = \sum_i H_{i,j}$$

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$$E[\alpha_j] = E[\sum_i H_{i,j}]$$

$$E[\alpha_j] = \sum_i Pr(H_{i,j} = 1) * 1 + Pr(H_{i,j} = 0) * 0$$

$$E[\alpha_j] = n * Pr(H_{i,j} = 1)$$

Separate Chaining Under SUHA

Table Size: m

Num objects: n

Claim: Under SUHA, expected length of chain is $\frac{n}{m}$

$\alpha_j =$ expected # of items hashing to position j

$$\alpha_j = \sum_i H_{i,j}$$

$$H_{i,j} = \begin{cases} 1 \text{ if item i hashes to j} \\ 0 \text{ otherwise} \end{cases}$$

$$E[\alpha_j] = E[\sum_i H_{i,j}]$$

$$Pr[H_{i,j} = 1] = \frac{1}{m}$$

$$E[\alpha_j] = n * Pr(H_{i,j} = 1)$$

Separate Chaining Under SUHA

Claim: Under SUHA, expected length of chain is $\frac{n}{m}$

Table Size: m

Num objects: n

α_j = expected # of items hashing to position j

$$\alpha_j = \sum_i H_{i,j}$$

$$H_{i,j} = \begin{cases} \text{1 if item i hashes to j} \\ \text{0 otherwise} \end{cases}$$

$$E[\alpha_j] = E[\sum_i H_{i,j}]$$

$$Pr[H_{i,j} = 1] = \frac{1}{m}$$

$$E[\alpha_j] = n * Pr(H_{i,j} = 1)$$

$$\mathbf{E}[\alpha_\mathbf{j}] = \frac{\mathbf{n}}{\mathbf{m}}$$

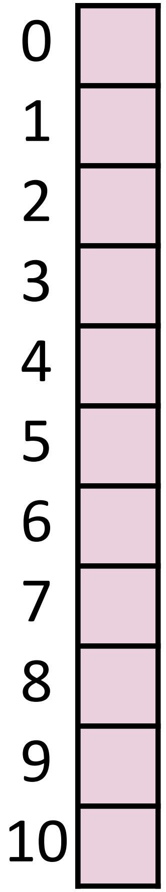
Separate Chaining Under SUHA

Under SUHA, a hash table of size *m* and *n* elements:

Find runs in: ___________.

Insert runs in: ___________.

Remove runs in: ___________.



Separate Chaining Under SUHA

Pros:

Cons:

Next time: Closed Hashing

Closed Hashing: store *k,v* pairs in the hash table

S = { 1, 8 , 15}

h(k) = k % 7