CS 106B, Lecture 27
Advanced Hashing

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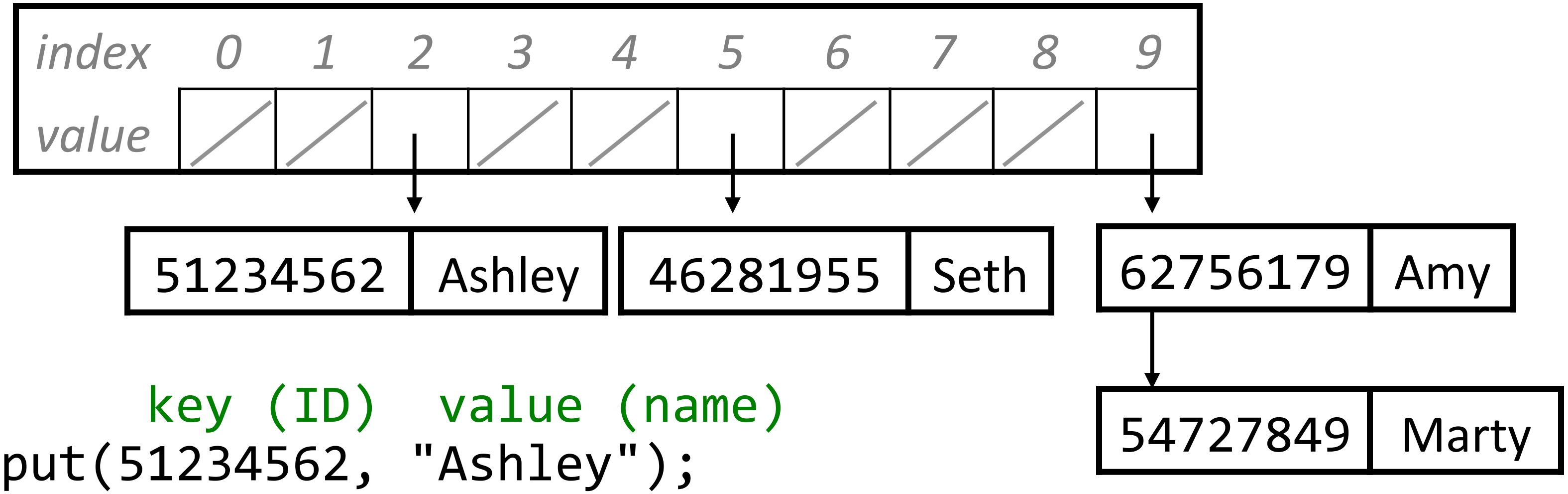
Based on slides created by Marty Stepp, Chris Gregg, Keith Schwarz, Julie Zelenski, Jerry Cain, Eric Roberts, Mehran Sahami, Stuart Reges, Cynthia Lee, and others

Plan for Today

- Discuss how HashMaps differ from HashSets
- Another implementation for HashSet/Map: Cuckoo Hashing!
- Discuss qualities of a good hash function.
- Learn about another application for hashing: cryptography.

Hash map (15.4)

- A hash map is like a set where the nodes store key/value pairs:



index	*0*	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
value	/	/		/	/		/	/	/	

51234562 Ashley

46281955 Seth

62756179 Amy

54727849 Marty

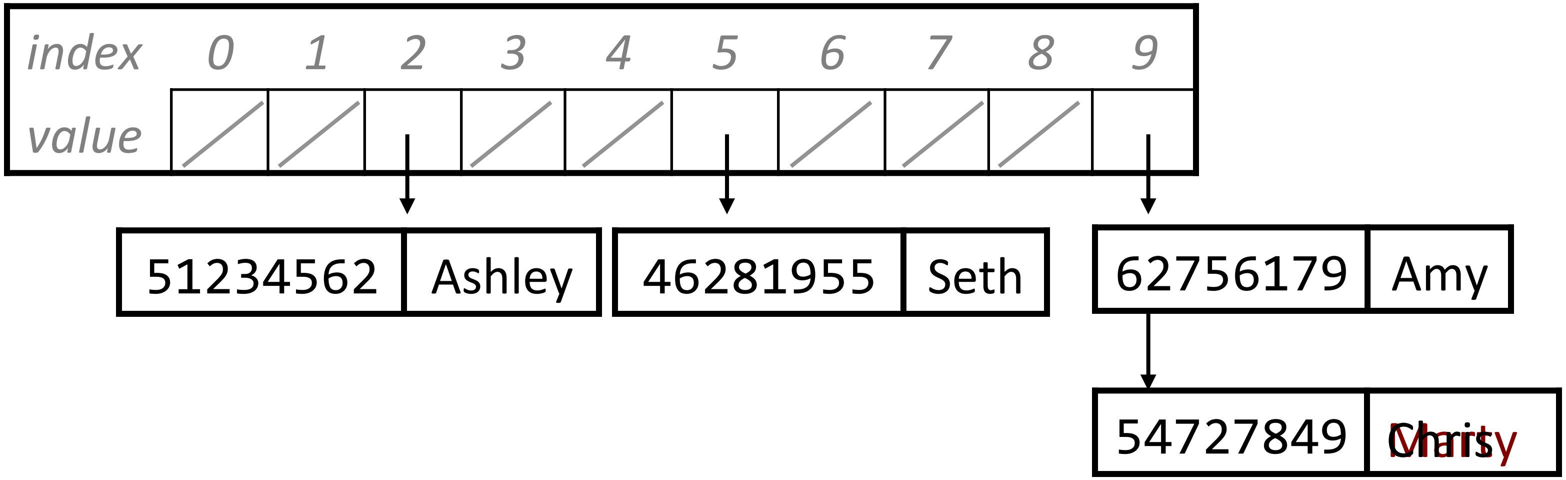
```
//         key (ID)  value (name)
map.put(51234562, "Ashley");
map.put(62756179, "Amy");
map.put(54727849, "Marty");
map.put(46281955, "Seth");
```

  – Must modify the HashNode class to store a key *and* a value

Hash map vs. hash set

- The hashing is always done on the keys, *not* the values.
- The `contains` function is now **`containsKey`**; there and in **`remove`**, you search for a node whose key matches a given key.
- The add method is now **`put`**; if the given key is already there, you must replace its old value with the new one.

```
map.put(54727849, "Chris");   // replace Marty with Chris
```



index	0	1	2	3	4	5	6	7	8	9
value	/	/		/	/		/	/	/	

51234562 | Ashley

46281955 | Seth

62756179 | Amy

54727849 | Chris

54727849 | Marty

Another Way to Hash

- Fun (but soon to be relevant) fact: cuckoo birds lay their eggs in other birds' nests

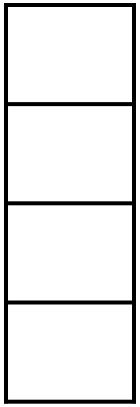
Source: wikimedia

Cuckoo Hashing

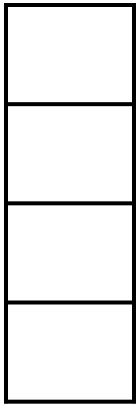
- What if we made contains **really** fast (look at at most two elements, no matter what)?
- Idea: have two arrays that store elements, where each array has its own hash function
- Try hashing the element into both arrays, and put it in an empty space
- If no space is empty, kick out one of the existing elements and move it to the other array.
- Contains just checks the corresponding spot in both arrays
- Slower add, but faster contains

Cuckoo Hashing

Insert: 3



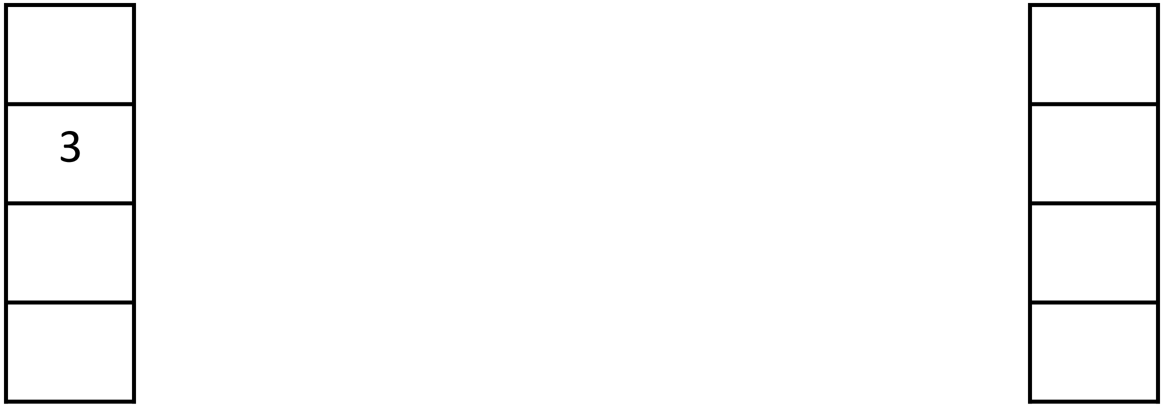
Hash Function: 3x % 4



Hash Function: (2x + 1) % 4

Cuckoo Hashing

Insert: 3

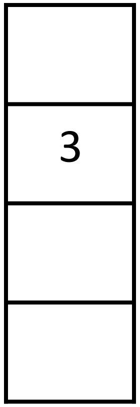


Hash Function: 3x % 4

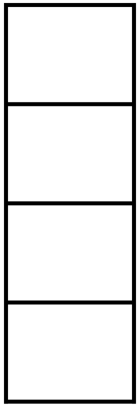
Hash Function: (2x + 1) % 4

Cuckoo Hashing

Insert: 6



Hash Function: 3x % 4



Hash Function: (2x + 1) % 4

Cuckoo Hashing

Insert: 6

3

Hash Function: 3x % 4

6

Hash Function: (2x + 1) % 4

Cuckoo Hashing

Insert: 5

3

Hash Function: 3x % 4

6

Hash Function: (2x + 1) % 4

Cuckoo Hashing

Insert: 5

3

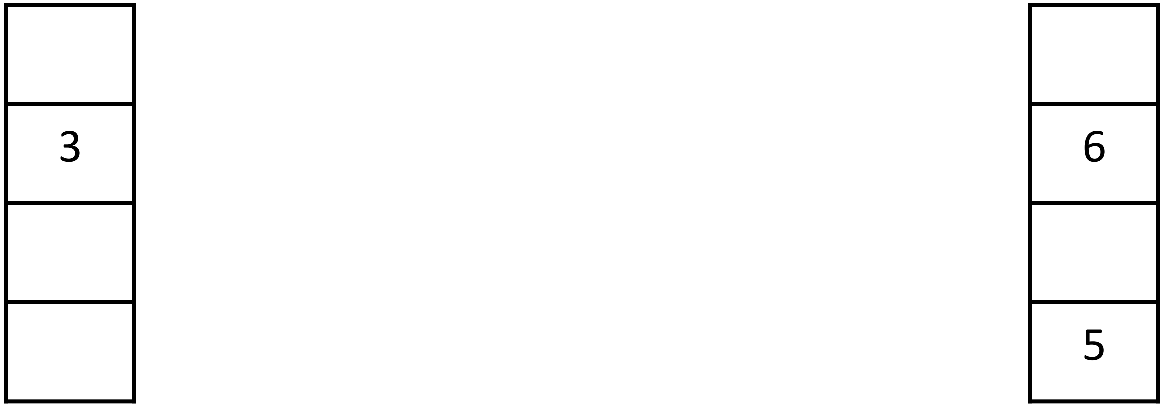
Hash Function: 3x % 4

6
5

Hash Function: (2x + 1) % 4

Cuckoo Hashing

Insert: 7



3

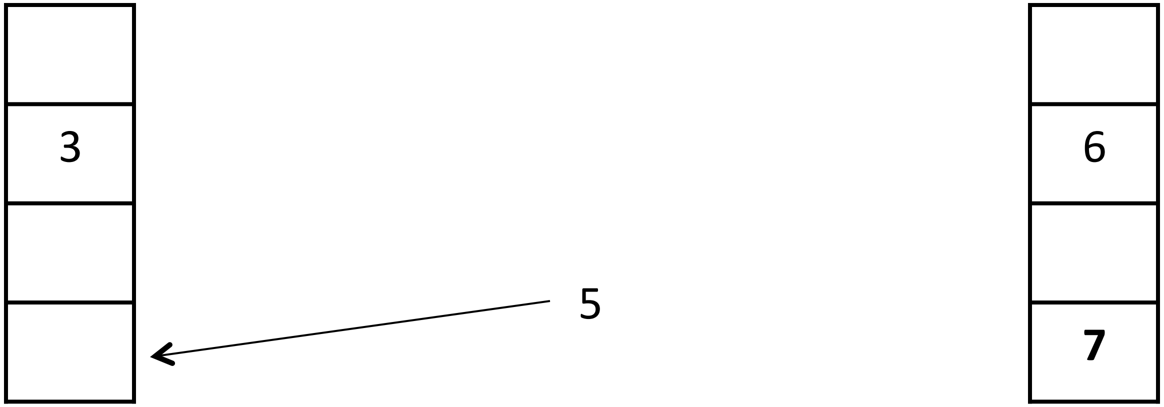
6
5

Hash Function: 3x % 4

Hash Function: (2x + 1) % 4

Cuckoo Hashing

Insert: 7

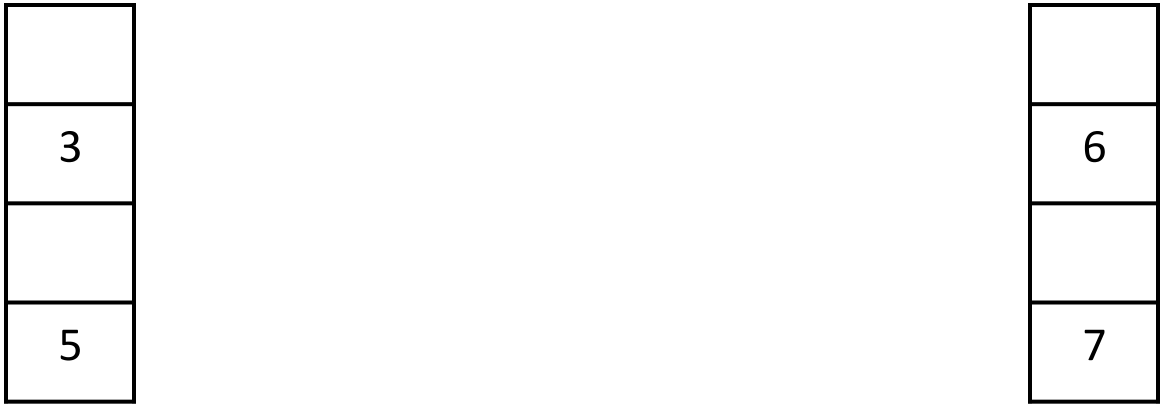


Hash Function: 3x % 4

Hash Function: (2x + 1) % 4

Cuckoo Hashing

Insert: 7

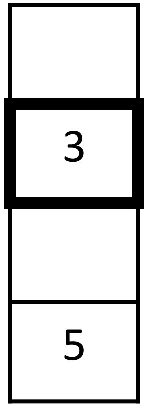


Hash Function: 3x % 4

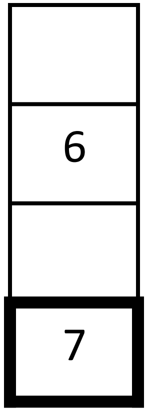
Hash Function: (2x + 1) % 4

Cuckoo Hashing

Search for 7 (look in both arrays)



Hash Function: 3x % 4



Hash Function: (2x + 1) % 4

Cuckoo Hashing

- What are the advantages or disadvantages of cuckoo hashing versus resolving collisions through chaining?
- What do we need to watch out for? When should we rehash?

Announcements

- Calligraphy announcements
  - Should start the 3rd part today or tomorrow at the latest
  - Starter code and Windows – please redownload
  - **No late days may be used, no late submissions accepted**
- Last class tomorrow – go to poll.ly/#/LdVNgWyo/G6z0awRv
- Final is a **on Saturday**, at 8:30AM, in **Cubberley Auditorium**
  - Everything from the course through today is fair game, emphasis is on second half materials (starting with pointers)
  - More information: https://web.stanford.edu/class/cs106b/exams/final.html
  - Practice exam is online – not guaranteed to match in format, etc.
  - Wednesday and Thursday will be final review
- Please give us feedback! cs198.stanford.edu

Hashing strings

- It is easy to hash an integer i (use index *abs(i) % length*).
  - How can we hash other types of values (such as strings)?

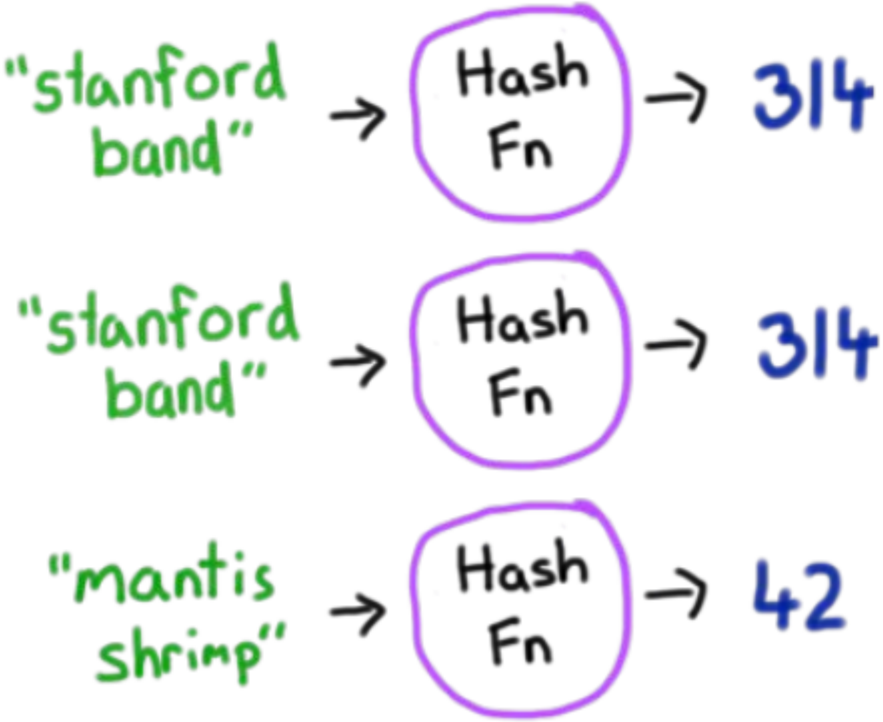
- If we could convert strings into integers, we could hash them.
  - What kind of integer is appropriate for a given string?
  - Does it matter what integer we choose? What should it be based on?

index	*0*	*1*	*2*	*3*	*4*	*5*	*6*	*7*
character	'H'	'i'	' '	'D'	'0'	'0'	'd'	'!'

hashCode consistency

- A valid hashCode function must be ***consistent***
  (must produce same results on each call)

`hashCode(x)  ==  hashCode(x)`, if **`x`**'s state doesn't change

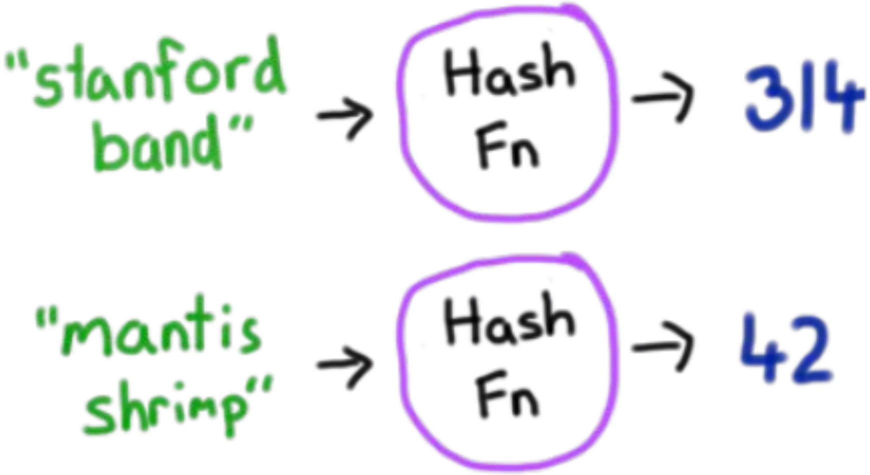


hashCode and equality

- A valid hashCode function must be ***consistent with equality.***

  a == b must imply that **hashCode(a) == hashCode(b)** .

```
Vector<int> v1;                 Vector<int> v2;
v1.add(1);                      v2.add(3);
v1.add(3);                      v2.insert(0, 1);
// hashCode(v1) == hashCode(v2)
```

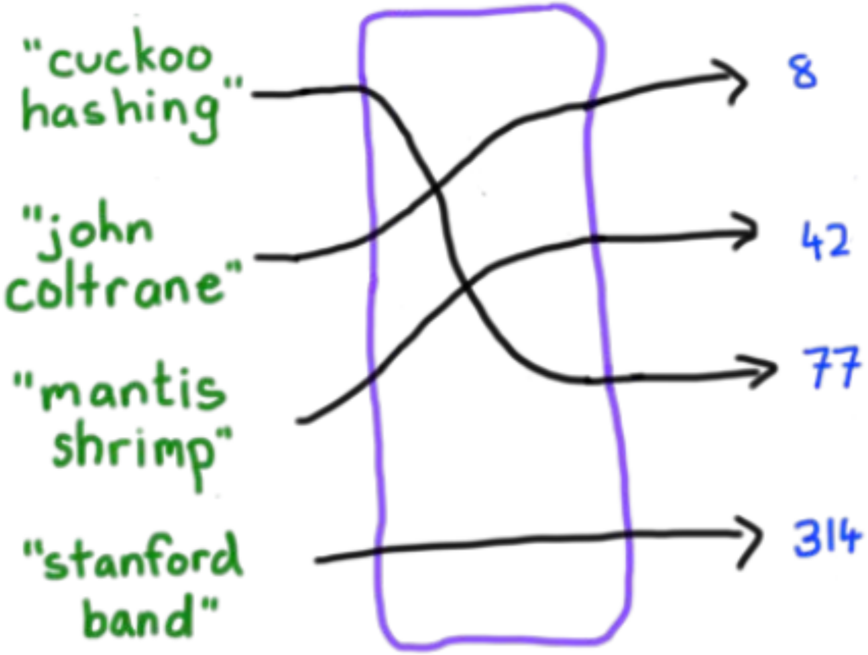


a != b does NOT necessarily imply that

hashCode(a) != hashCode(b) *(why not?)*

hashCode distribution

- A **good** hashCode function is ***well-distributed***.
  - For a large set of distinct values, they should generally return unique hash codes rather than often colliding into the same hash bucket.
  - This property is desired but not required. Why?



Possible hashCode 1

- **Q:** Is this a valid hash function? Is it good?

0	1	2	3	4	5	6	7
H	i		D	0	0	d	!

```
int hashCode(string s) { // #1
    return 42;
}
```

Possible hashCode 2

- **Q:** Is this a valid hash function? Is it good?

0	1	2	3	4	5	6	7
H	i		D	0	0	d	!

```
int hashCode(string s) { // #2
    return randomInteger(0, 9999999);
}
```

Possible hashCode 3

- **Q:** Is this a valid hash function? Is it good?

0	1	2	3	4	5	6	7
H	i		D	0	0	d	!

```
int hashCode(string s) { // #3
    return (int) &s;   // address of s (a pointer)
}
```

Possible hashCode 4

0	1	2	3	4	5	6	7
H	i		D	0	0	d	!

- **Q:** Is this a valid hash function? Is it good?

```
int hashCode(string s) { // #4
    return s.length();
}
```

Possible hashCode 5

- **Q:** Is this a valid hash function? Is it good?

0	1	2	3	4	5	6	7
H	i		D	0	0	d	!

```
int hashCode(string s) { // #5
    if (s.length() > 0) {
        return (int) s[0];   // ascii of 1st char
    } else {
        return 0;
    }
}
```

Possible hashCode 6

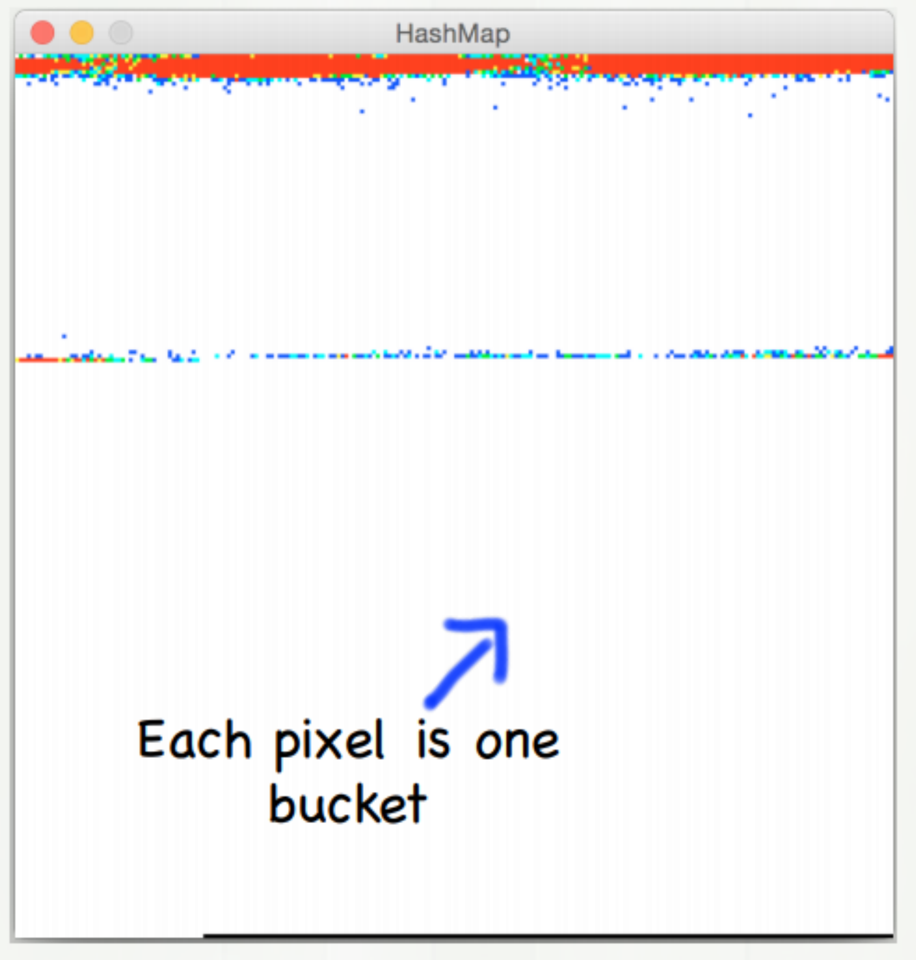
- This function sums the characters' ASCII values.
  - Is it valid? Is it good?
  - What will collide?

0	1	2	3	4	5	6	7
H	i		D	0	0	d	!

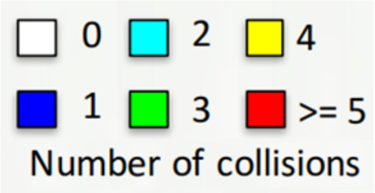
```
int hashCode(string s) { // #6
    int hash = 0;
    for (int i = 0; i < s.length(); i++) {
        hash += (int) s[i];   // ASCII of char
    }
    return hash;
}
```

Measuring collisions

- Hash function = sum of characters of string.
- Add 50,000,000 article titles to a hash map with 50,000 buckets:



Each pixel is one bucket



Idea: Weighted sum

hash = s[0] + s[1] + s[2] + ... + s[n]

- Instead of adding, let's give each character a **weight**.
  - Multiply it by increasing powers of some prime number; say, 31.
  - This helps spread the strings' hash codes over the range of int values.

hash = s[0] + (31 * s[1]) + (31^2 * s[2]) + ... + (31^n * s[n])

hashCode for strings

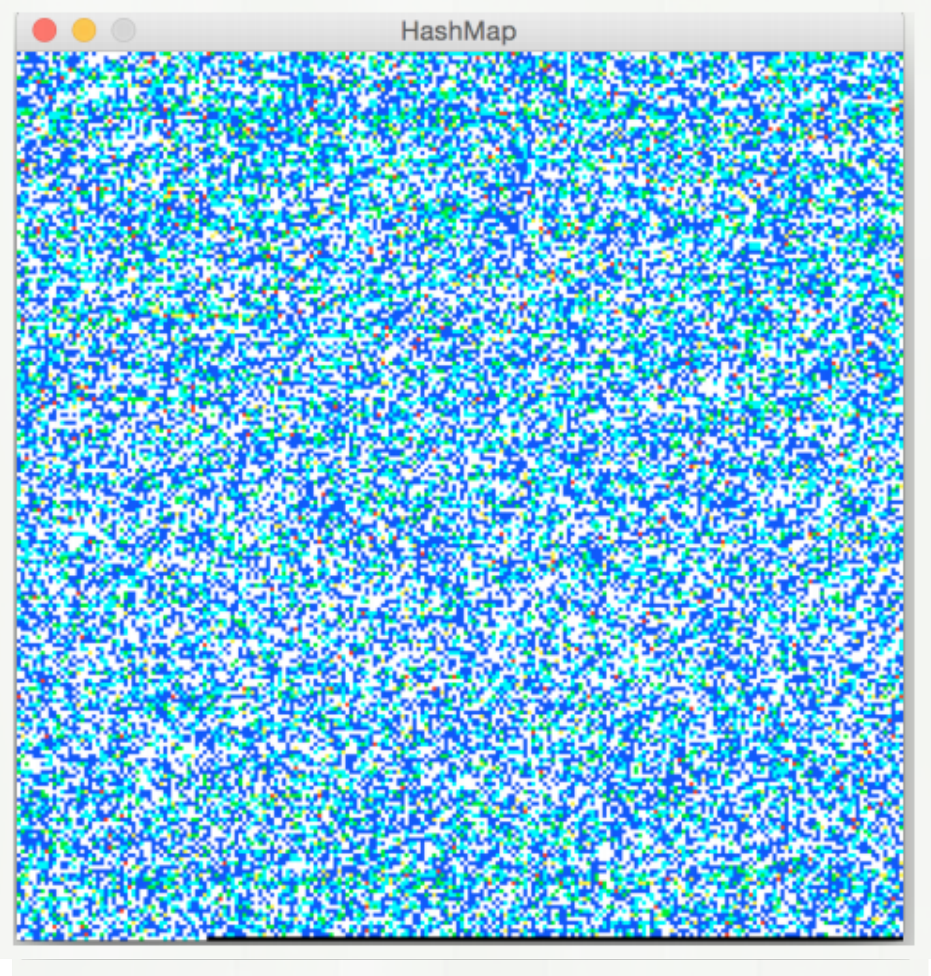
```
int hashCode(string s) {
    int hash = 5381;
    for (int i = 0; i < (int) s.length(); i++) {
        hash = 31 * hash + (int) s[i];
    }
    return hash;
}
```

- FYI: The above is the actual hash function used for strings in Java.

- As with any general hashing function, collisions are possible.
  - Example: "Ea" and "FB" have the same hash value.

Measuring collisions

- Hash function = sum of characters of string, **multiplying by 31**.
- Add 50,000,000 article titles to a hash map with 50,000 buckets:



⬜ 0 🟦 2 🟨 4

🟦 1 🟩 3 🟥 >= 5

Number of collisions

Hashing structs/objects

- By default you cannot add your own structs/objects to hash sets.
  - Our libraries don't know how to hash these objects.

```
struct Point {
    int x;
    int y;
    ...
};

HashSet<Point> hset;
Point p {17, 35};
hset.add(p);

ERROR: no matching function for call to
'hashCode(const Point&)'
```

Hashing structs/objects

- To make your own types hashable by our libraries:
  - 1) Overload the **== operator**.
  - 2) Write a **hashCode function** that takes your type as its parameter.
    - "Add up" the object's state; scale/multiply parts to distribute the results.

```
struct Point {
    int x;
    int y;
    ...
};

int hashCode(const Point& p) {
    return 1337 * p.y + 31 * p.x;
}

bool operator ==(const Point& p1, const Point& p2) {
    return p1.x == p2.x && p1.y == p2.y;
}
```

Hashing and Passwords

- We want to store a file of user passwords
  - When a user types a password, see if it matches our file
- Problem: anyone who can see our file can get all the passwords

User	**Password**
Ashley	password123
Shreya	traceComics
Seth	ki88leLuv

Hashing and Passwords

- What if we stored a unique code for each password instead of the string?
  - Hashing!
- Extra requirements for the hash function:
  - Want a large number of possible values (hard to find collisions)
  - Can’t find the password from the hash (one-way)
  - Generally use a different hash function (e.g. SHA-256)
- The need for salting

User	**Password**
Ashley	17851691385
Marty	63158910316
Amy	90713593110

Hashing and Data Integrity

- A common "attack" in cryptography is man-in-the-middle
- How can you ensure that a hacker didn't interfere with the data?
- Get the hash from a **trusted** source – since hash functions only rarely have collisions, changes to data will lead to a different hash