CSE 373: Hash functions and hash tables

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Monday, Jan 22, 2018

Warmup

Warmup: Consider the following method.

```java
private int mystery(int x) {
    if (x <= 10) {
        return 5;
    } else {
        int foo = 0;
        for (int i = 0; i < x; i++)
            foo += x;
        return foo + (2 * mystery(x - 1)) + (3 * mystery(x - 2));
    }
}
```

$$T(x) = \begin{cases} 1 & \text{if } x \le 10 \\ x + T(x-1) + T(x-2) & \text{otherwise} \end{cases}$$

$$M(x) = \begin{cases} 5 & \text{if } x \le 10 \\ \left[\sum_{i=0}^{x-1} x\right] + 2T(x-1) + 3T(x-2) & \text{otherwise} \end{cases}$$

$foo = x + x + x$

$foo = \sum_{i=0}^{x-1} x$

With your neighbor, answer the following.

1. Construct a mathematical formula $T(x)$ modeling the *worst-case runtime* of this method.
2. Construct a mathematical formula $M(x)$ modeling the *integer output* of this method.

$M(5) == mystery(5)$

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Today's plan:

Goal: Learn how to implement a hash map

Plan of attack:

1. Implement a limited, but efficient dictionary
2. Gradually remove each limitation, *adapting* our original
3. Finish with an efficient and general-purpose dictionary

Implementing `FinitePositiveIntegerDictionary`

Step 1:

Implement a dictionary that accepts only *integer* keys between 0 and some k.

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How would you implement `get`, `put`, and `remove` so they all work in $\Theta(1)$ time?

Hint: first consider what underlying data structure(s) to use. An array? Something using nodes? (E.g. a linked list or a tree).

Implementing FinitePositiveIntegerDictionary

Solution: Create and maintain an internal array of size k.

Map each key to the corresponding index in array:

```
public V get(int key) {
    this.ensureIndexNotNull(key);
    return this.array[key].value;
}

public void put(int key, V value) {
    this.array[key] = new Pair<>(key, value);
}

public void remove(int key) {
    this.ensureIndexNotNull(key);
    this.array[key] = null;
}

private void ensureIndexNotNull(int index) {
    if (this.array[index] == null) {
        throw new NoSuchKeyException();
    }
}
```

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What's the problem?

- Can we even allocate an array that big?
- Potentially very wasteful: what if our data is sparse?
  This is also a problem with our
  `FinitePositiveIntegerDictionary`!

Step 2:

Implement a dictionary that accepts **any** *integer* key.

Idea 2: Create a smaller array, and mod the key by array length.

So, instead of looking at `this.array[key]`, we look at `this.array[key % this.array.length]`.

A brief interlude on mod:

The “modulus” (mod) operation

In math, “$a \bmod b$” is the remainder of *a* divided by *b*.*
Both *a* and *b* MUST be integers.

In Java, we write this as `a % b`.

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Examples (in Java syntax)

- `28 % 5 == 3`
- `427 % 100 == 27`
- `8 % 8 == 0`
- `2 % 8 == 2`

Useful when you want "wrap-around" behavior, or want an integer to stay within a certain range.

Implementing IntegerDictionary

Idea 2: Create a smaller array, and mod the key by array length.

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public V get(int key) {
    int newKey = key % this.array.length;
    this.ensureIndexNotNull(newKey);
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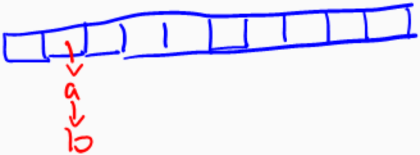

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What's the bug here?

Implementing `IntegerDictionary`: resolving collisions

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Suppose the array has length 10 and we insert the key-value pairs $(8, \text{"foo"})$ and $(18, \text{"bar"})$. What does the dictionary look like?

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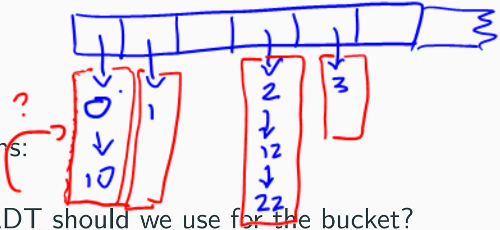

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2. What's the *worst-case* runtime of our dictionary, assuming we implement the bucket using a linked list?

Implementing `IntegerDictionary`

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1. What ADT should we use for the bucket?
   A dictionary!
2. What's the *worst-case* runtime of our dictionary, assuming we implement the bucket using a linked list?
   $\Theta(n)$ – what if everything gets stored in the same bucket?

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Let n be the total number of key-value pairs.

Let c be the capacity of the internal array.

The "load factor" λ is $\lambda = \frac{n}{c}$.

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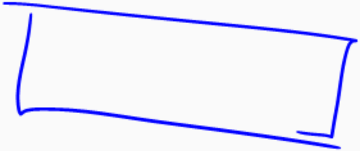
Assuming we use a linked list for our bucket, the *average* runtime of our dictionary operations is $\Theta(1 + \lambda)$!

Implementing IntegerDictionary: improving performance

Goal: Improve the *average* runtime of our IntegerDictionary

Ideas:

- Right now, we can't do anything about the keys we get.
- Can we modify the bucket somehow?
- Can we modify the array's internal capacity somehow?



what if capacity = 10
and we insert 20 keys?
100 keys?

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Important: When separate chaining, we should keep $\lambda \approx 1.0$.

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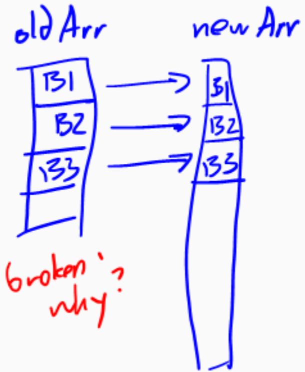
- Just double the size of the array
- Increase the array size to the next prime number that's (roughly) double the array size



Three question:

1. How do you resize the array?
2. What's the runtime of resizing?
3. Why use prime numbers?

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    - How can we avoid using a lot of memory?
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1. Implement a finite, positive integer dictionary
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    - How can we avoid using a lot of memory?
    - How do we handle collisions?
    - How do we keep the *average* performance $\Theta(1)$?
3. Implement a general-purpose dictionary

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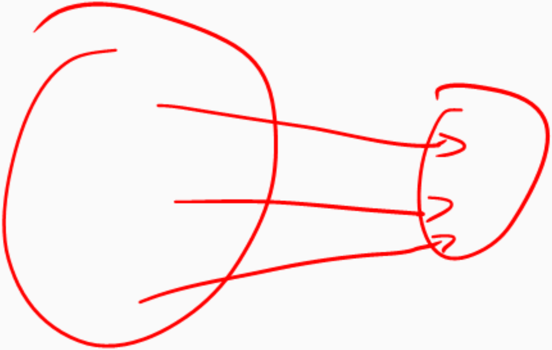
Solution: Use a hash function!

Hash function

A hash function is a mapping from the key set U to an integer.



Hash functions

There are many different properties a hash function could have.

Using hash functions inside dictionaries: useful properties

A hash function that is intended to be used for a dictionary should ideally have the following properties:

- **Uniform distribution of outputs:**
  In Java, there are 2^{32} 32-bit ints. So, the probability that the hash function returns any individual int should be $\frac{1}{2^{32}}$.

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- **Low collision rate:**
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  We want to *minimize collisions* as much as possible.
- **Low computational cost:**
  We will be computing the hash function a lot, so we need it to be very easy to compute.

Exercise: hash function for strings

Analyze these hash function implementations.

- $h(s) = 1$
- $h(s) = \sum_{i=0}^{|s|-1} s_i$
- $h(s) = 2^{s_0} \cdot 3^{s_1} \cdot 5^{s_2} \cdot 7^{s_3} \cdots$
- $h(s) = \sum_{i=0}^{|s|-1} 31^i \cdot s_i$

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- Midterm on Friday, Feb 2, in-class
  - Review session time and locations TBD
    (but probably Mon 29 and Tues 30?)
  - More details on Wednesday