BBM 202 - ALGORITHMS

HACETTEPE UNIVERSITY

DEPT. OF COMPUTER ENGINEERING

HASHING, SEARCH APPLICATIONS

Acknowledgement: The course slides are adapted from the slides prepared by R. Sedgewick and K. Wayne of Princeton University.

ST implementations: summary

implementation	worst-case cost (after N inserts)			average-case cost (after N random inserts)			ordered iteration?	key interface
	search	insert	delete	search hit	insert	delete		
sequential search (unordered list)	N	N	N	N/2	N	N/2	no	`equals()`
binary search (ordered array)	lg N	N	N	lg N	N/2	N/2	yes	`compareTo()`
BST	N	N	N	1.38 lg N	1.38 lg N	?	yes	`compareTo()`
red-black BST	2 lg N	2 lg N	2 lg N	1.00 lg N	1.00 lg N	1.00 lg N	yes	`compareTo()`

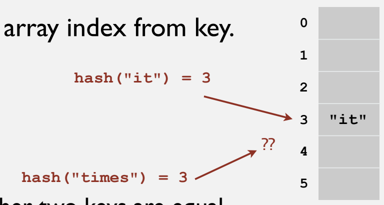
Q. Can we do better?

A. Yes, but with different access to the data (if we don't need ordered ops).

Hashing: basic plan

Save items in a key-indexed table (index is a function of the key).

Hash function. Method for computing array index from key.



Issues.

- Computing the hash function.
- Equality test: Method for checking whether two keys are equal.
- Collision resolution: Algorithm and data structure to handle two keys that hash to the same array index.

Classic space-time tradeoff.

- No space limitation: trivial hash function with key as index. Very large index table, few collisions
- No time limitation: trivial collision resolution with sequential search. Small table, lots of collisions, must search within the cell.
- Space and time limitations: hashing (the real world).

HASHING

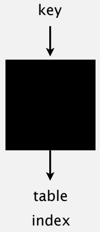
- Hash functions
- Separate chaining
- Linear probing

Computing the hash function

Idealistic goal. Scramble the keys uniformly to produce a table index.

- Efficiently computable.
- Each table index equally likely for each key.

thoroughly researched problem, still problematic in practical applications



Ex 1. Phone numbers.

- Bad: first three digits.
- Better: last three digits.

Ex 2. Social Security numbers.

- Bad: first three digits.
- Better: last three digits.

573 = California, 574 = Alaska
(assigned in chronological order within geographic region)

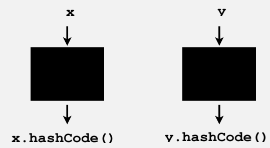
Practical challenge. Need different approach for each key type.

Java's hash code conventions

All Java classes inherit a method `hashCode()`, which returns a 32-bit `int`.

Requirement. If `x.equals(y)`, then `(x.hashCode() == y.hashCode())`.

Highly desirable. If `!x.equals(y)`, then `(x.hashCode() != y.hashCode())`.



Default implementation. Memory address of `x`.
Legal (but poor) implementation. Always return `17`.
Customized implementations. `Integer`, `Double`, `String`, `File`, `URL`, `Date`, ...
User-defined types. Users are on their own.

Implementing hash code: integers, booleans, and doubles

Java library implementations

```
public final class Integer
{
   private final int value;
   ...

   public int hashCode()
   {  return value;  }
}
```

```
public final class Double
{
   private final double value;
   ...

   public int hashCode()
   {
      long bits = doubleToLongBits(value);
      return (int) (bits ^ (bits >>> 32));
   }
}
```

convert to IEEE 64-bit representation;
xor most significant 32-bits
with least significant 32-bits

```
public final class Boolean
{
   private final boolean value;
   ...

   public int hashCode()
   {
      if (value) return 1231;
      else       return 1237;
   }
}
```


Implementing hash code: strings

Java library implementation

```
public final class String
{
   private final char[] s;
   ...

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

i^{th} character of s

char	Unicode
…	…
'a'	97
'b'	98
'c'	99
…	...

- Horner's method to hash string of length L: L multiplies/adds.
- Equivalent to $h = s[0] \cdot 31^{L-1} + \ldots + s[L-3] \cdot 31^2 + s[L-2] \cdot 31^1 + s[L-1] \cdot 31^0$.

Ex.

```
String s = "call";
int code = s.hashCode();
```

$3045982 = 99 \cdot 31^3 + 97 \cdot 31^2 + 108 \cdot 31^1 + 108 \cdot 31^0$
$= 108 + 31 \cdot (108 + 31 \cdot (97 + 31 \cdot (99)))$
(Horner's method)

Implementing hash code: strings

Performance optimization.

- Cache the hash value in an instance variable.
- Return cached value.

```
public final class String
{
   private int hash = 0;
   private final char[] s;
   ...

   public int hashCode()
   {
      int h = hash;
      if (h != 0) return h;
      for (int i = 0; i < length(); i++)
         h = s[i] + (31 * h);
      hash = h;
      return h;
   }
}
```

cache of hash code (`private int hash = 0;`)

return cached value (`int h = hash; if (h != 0) return h;`)

store cache of hash code (`hash = h;`)

Implementing hash code: user-defined types

```
public final class Transaction implements Comparable<Transaction>
{
   private final String  who;
   private final Date    when;
   private final double  amount;

   public Transaction(String who, Date when, double amount)
   {  /* as before */  }

   ...

   public boolean equals(Object y)
   {  /* as before */  }

   public int hashCode()
   {
      int hash = 17;
      hash = 31*hash + who.hashCode();
      hash = 31*hash + when.hashCode();
      hash = 31*hash + ((Double) amount).hashCode();
      return hash;
   }
}
```

nonzero constant (17)

typically a small prime (31)

for reference types, use `hashCode()`

for primitive types, use `hashCode()` of wrapper type

Hash code design

"Standard" recipe for user-defined types.

- Combine each significant field using the $31x + y$ rule.
- If field is a primitive type, use wrapper type `hashCode()`.
- If field is null, return 0.
- If field is a reference type, use `hashCode()`. ← applies rule recursively
- If field is an array, apply to each entry. ← or use `Arrays.deepHashCode()`

In practice. Recipe works reasonably well; used in Java libraries.

In theory. Keys are bitstring; "universal" hash functions exist.

Basic rule. Need to use the whole key to compute hash code; consult an expert for state-of-the-art hash codes.

Modular hashing

Hash code. An `int` between -2^{31} and $2^{31}-1$.

Hash function. An `int` between `0` and `M-1` (for use as array index).

typically a prime or power of 2 (M)

```
private int hash(Key key)
{  return key.hashCode() % M;  }
```

bug

```
private int hash(Key key)
{  return Math.abs(key.hashCode()) % M;  }
```

1-in-a-billion bug

hashCode() of "polygenelubricants" is -2^{31}

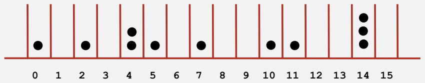
```
private int hash(Key key)
{  return (key.hashCode() & 0x7fffffff) % M;  }
```

correct

Uniform hashing assumption

Uniform hashing assumption. Each key is equally likely to hash to an integer between 0 and $M - 1$.

Bins and balls. Throw balls uniformly at random into M bins.



Birthday problem. Expect two balls in the same bin after $\sim\sqrt{\pi M / 2}$ tosses.

Coupon collector. Expect every bin has ≥ 1 ball after $\sim M \ln M$ tosses.

Load balancing. After M tosses, expect most loaded bin has $\Theta(\log M / \log \log M)$ balls.

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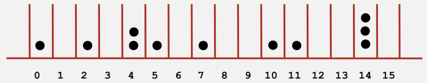


Hash value frequencies for words in Tale of Two Cities (M = 97)

Java's `String` data uniformly distribute the keys of Tale of Two Cities

HASHING

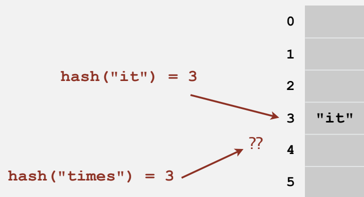
- Hash functions
- **Separate chaining**
- Linear probing

Collisions

Collision. Two distinct keys hashing to same index.

- Birthday problem $\Rightarrow$ can't avoid collisions unless you have a ridiculous (quadratic) amount of memory.
- Coupon collector + load balancing $\Rightarrow$ collisions will be evenly distributed.

Challenge. Deal with collisions efficiently.

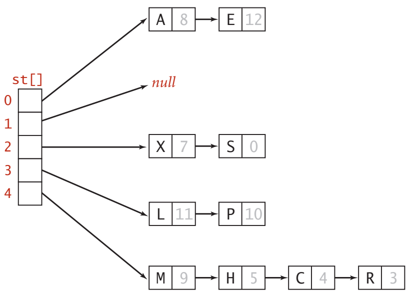


Separate chaining symbol table

Use an array of $M < N$ linked lists. [H. P. Luhn, IBM 1953]

- Hash: map key to integer i between 0 and $M - 1$.
- Insert: put at front of i^{th} chain (if not already there).
- Search: need to search only i^{th} chain.

key	hash	value
S	2	0
E	0	1
A	0	2
R	4	3
C	4	4
H	4	5
E	0	6
X	2	7
A	0	8
M	4	9
P	3	10
L	3	11
E	0	12



Separate chaining ST: Java implementation

```
public class SeparateChainingHashST<Key, Value>
{
   private int M = 97;                  // number of chains
   private Node[] st = new Node[M];     // array of chains

   private static class Node
   {
      private Object key;
      private Object val;
      private Node next;
      ...
   }

   private int hash(Key key)
   {  return (key.hashCode() & 0x7fffffff) % M;  }

   public Value get(Key key) {
      int i = hash(key);
      for (Node x = st[i]; x != null; x = x.next)
         if (key.equals(x.key)) return (Value) x.val;
      return null;
   }

}
```

array doubling and halving code omitted

no generic array creation (declare key and value of type Object)

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```
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   private static class Node
   {
      private Object key;
      private Object val;
      private Node next;
      ...
   }

   private int hash(Key key)
   {  return (key.hashCode() & 0x7fffffff) % M;  }

   public void put(Key key, Value val) {
      int i = hash(key);
      for (Node x = st[i]; x != null; x = x.next)
         if (key.equals(x.key)) { x.val = val; return; }
      st[i] = new Node(key, val, st[i]);
   }

}
```
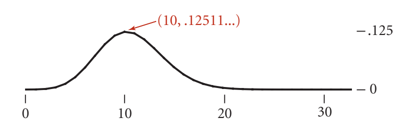


Analysis of separate chaining

Proposition. Under uniform hashing assumption, probability that the number of keys in a list is within a constant factor of N / M is extremely close to 1.

Pf sketch. Distribution of list size obeys a binomial distribution.



Binomial distribution ($N = 10^4$, $M = 10^3$, $\alpha = 10$)

equals() and hashCode()

Consequence. Number of probes for search/insert is proportional to N / M.

- M too large $\Rightarrow$ too many empty chains.
- M too small $\Rightarrow$ chains too long.
- Typical choice: $M \sim N / 5$ $\Rightarrow$ constant-time ops.

M times faster than sequential search

ST implementations: summary

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binary search (ordered array)	lg N	N	N	lg N	N/2	N/2	yes	`compareTo()`
BST	N	N	N	1.38 lg N	1.38 lg N	?	yes	`compareTo()`
red-black tree	2 lg N	2 lg N	2 lg N	1.00 lg N	1.00 lg N	1.00 lg N	yes	`compareTo()`
separate chaining	N *	N *	N *	3-5 *	3-5 *	3-5 *	no	`equals()`

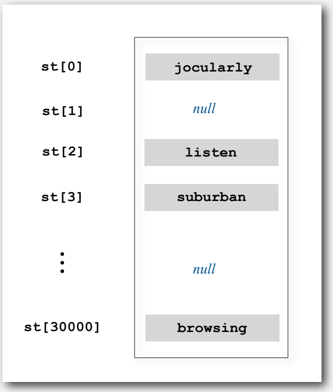
* under uniform hashing assumption

HASHING

- Hash functions
- Separate chaining
- Linear probing

Collision resolution: open addressing

Open addressing. [Amdahl-Boehme-Rocherster-Samuel, IBM 1953]
When a new key collides, find next empty slot, and put it there.

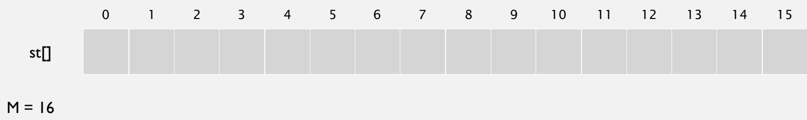


linear probing (M = 30001, N = 15000)

Linear probing hash table

Hash. Map key to integer i between 0 and $M - 1$.
Insert. Put at table index i if free; if not try $i + 1$, $i + 2$, etc.

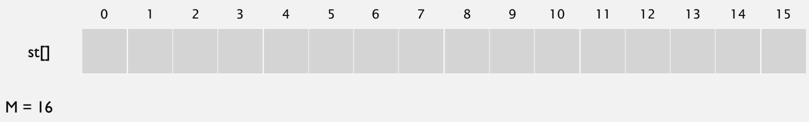
linear probing hash table



Linear probing hash table

Hash. Map key to integer i between 0 and $M - 1$.
Insert. Put at table index i if free; if not try $i + 1$, $i + 2$, etc.

insert S
hash(S) = 6



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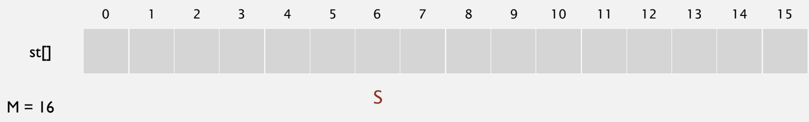

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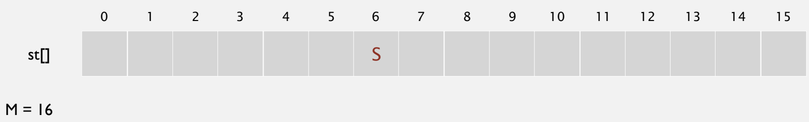

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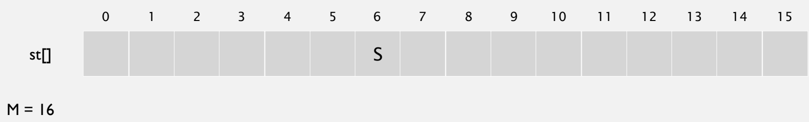

Linear probing hash table

Hash. Map key to integer i between 0 and $M - 1$.

Insert. Put at table index i if free; if not try $i + 1$, $i + 2$, etc.

insert E
hash(E) = 10

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
st[]							S									

M = 16

Linear probing hash table

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linear probing hash table

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st[]							S				E					

M = 16

Linear probing hash table

Hash. Map key to integer i between 0 and $M - 1$.

Insert. Put at table index i if free; if not try $i + 1$, $i + 2$, etc.

insert A

hash(A) = 4

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
st[]							S				E					

M = 16

Linear probing hash table

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linear probing hash table

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st[]					A		S				E					

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Linear probing hash table

Hash. Map key to integer i between 0 and $M - 1$.
Insert. Put at table index i if free; if not try $i + 1$, $i + 2$, etc.

insert R
hash(R) = 14

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
st[]					A		S				E					

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Linear probing hash table

Hash. Map key to integer i between 0 and $M - 1$.
Insert. Put at table index i if free; if not try $i + 1$, $i + 2$, etc.

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hash(R) = 14

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
st[]					A		S				E					
															R	

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Insert. Put at table index i if free; if not try $i + 1$, $i + 2$, etc.

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hash(R) = 14

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linear probing hash table

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Linear probing hash table

Hash. Map key to integer i between 0 and $M - 1$.

Insert. Put at table index i if free; if not try $i + 1$, $i + 2$, etc.

insert C
hash(C) = 5

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
st[]					A		S				E				R	

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linear probing hash table

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hash(H) = 4

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Linear probing hash table

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Insert. Put at table index i if free; if not try $i + 1$, $i + 2$, etc.

insert X
hash(X) = 15

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
st[]					A	C	S	H			E				R	

M = 16

Linear probing hash table

Hash. Map key to integer i between 0 and $M - 1$.

Insert. Put at table index i if free; if not try $i + 1$, $i + 2$, etc.

insert X

hash(X) = 15

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
st[]					A	C	S	H			E				R	
																X

M = 16

Linear probing hash table

Hash. Map key to integer i between 0 and $M - 1$.

Insert. Put at table index i if free; if not try $i + 1$, $i + 2$, etc.

insert X

hash(X) = 15

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
st[]					A	C	S	H			E				R	X

M = 16

Linear probing hash table

Hash. Map key to integer i between 0 and $M - 1$.

Insert. Put at table index i if free; if not try $i + 1$, $i + 2$, etc.

linear probing hash table

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
st[]					A	C	S	H			E				R	X

M = 16

Linear probing hash table

Hash. Map key to integer i between 0 and $M - 1$.

Insert. Put at table index i if free; if not try $i + 1$, $i + 2$, etc.

insert M

hash(M) = 1

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
st[]					A	C	S	H			E				R	X

M = 16

Linear probing hash table

Hash. Map key to integer i between 0 and $M - 1$.

Insert. Put at table index i if free; if not try $i + 1$, $i + 2$, etc.

insert M
hash(M) = 1

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
st[]					A	C	S	H			E				R	X
M = 16		M														

Linear probing hash table

Hash. Map key to integer i between 0 and $M - 1$.

Insert. Put at table index i if free; if not try $i + 1$, $i + 2$, etc.

insert M
hash(M) = 1

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
st[]		M			A	C	S	H			E				R	X

M = 16

Linear probing hash table

Hash. Map key to integer i between 0 and $M - 1$.

Insert. Put at table index i if free; if not try $i + 1$, $i + 2$, etc.

linear probing hash table

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
st[]		M			A	C	S	H			E				R	X

M = 16

Linear probing hash table

Hash. Map key to integer i between 0 and $M - 1$.

Insert. Put at table index i if free; if not try $i + 1$, $i + 2$, etc.

insert P
hash(P) = 14

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
st[]		M			A	C	S	H			E				R	X

M = 16

Linear probing hash table

Hash. Map key to integer i between 0 and $M - 1$.
Insert. Put at table index i if free; if not try $i + 1$, $i + 2$, etc.

insert P
hash(P) = 14

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
st[]		M			A	C	S	H			E				R	X
															P	

M = 16

Linear probing hash table

Hash. Map key to integer i between 0 and $M - 1$.
Insert. Put at table index i if free; if not try $i + 1$, $i + 2$, etc.

insert P
hash(P) = 14

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
st[]		M			A	C	S	H			E				R	X
	P															P

M = 16

Linear probing hash table

Hash. Map key to integer i between 0 and $M - 1$.
Insert. Put at table index i if free; if not try $i + 1$, $i + 2$, etc.

insert P
hash(P) = 14

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
st[]	P	M			A	C	S	H			E				R	X

M = 16

Linear probing hash table

Hash. Map key to integer i between 0 and $M - 1$.
Insert. Put at table index i if free; if not try $i + 1$, $i + 2$, etc.

linear probing hash table

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
st[]	P	M			A	C	S	H			E				R	X

M = 16

Linear probing hash table

Hash. Map key to integer i between 0 and $M - 1$.
Insert. Put at table index i if free; if not try $i + 1$, $i + 2$, etc.

insert L
hash(L) = 6

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
st[]	P	M			A	C	S	H			E				R	X

M = 16

Linear probing hash table

Hash. Map key to integer i between 0 and $M - 1$.
Insert. Put at table index i if free; if not try $i + 1$, $i + 2$, etc.

insert L
hash(L) = 6

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
st[]	P	M			A	C	S	H			E				R	X
							L									

M = 16

Linear probing hash table

Hash. Map key to integer i between 0 and $M - 1$.
Insert. Put at table index i if free; if not try $i + 1$, $i + 2$, etc.

insert L
hash(L) = 6

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
st[]	P	M			A	C	S	H			E				R	X
								L								

M = 16

Linear probing hash table

Hash. Map key to integer i between 0 and $M - 1$.
Insert. Put at table index i if free; if not try $i + 1$, $i + 2$, etc.

insert L
hash(L) = 6

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
st[]	P	M			A	C	S	H			E				R	X
									L							

M = 16

Linear probing hash table

Hash. Map key to integer i between 0 and $M - 1$.
Insert. Put at table index i if free; if not try $i + 1$, $i + 2$, etc.

insert L
hash(L) = 6

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
st[]	P	M			A	C	S	H	L		E				R	X

M = 16

Linear probing hash table

Hash. Map key to integer i between 0 and $M - 1$.
Insert. Put at table index i if free; if not try $i + 1$, $i + 2$, etc.

linear probing hash table

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
st[]	P	M			A	C	S	H	L		E				R	X

M = 16

Linear probing hash table

Hash. Map key to integer i between 0 and $M - 1$.
Insert. Put at table index i if free; if not try $i + 1$, $i + 2$, etc.
Search. Search table index i; if occupied but no match, try $i + 1$, $i + 2$, etc.

linear probing hash table

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
st[]	P	M			A	C	S	H	L		E				R	X

M = 16

Linear probing hash table

Hash. Map key to integer i between 0 and $M - 1$.
Insert. Put at table index i if free; if not try $i + 1$, $i + 2$, etc.
Search. Search table index i; if occupied but no match, try $i + 1$, $i + 2$, etc.

search E
hash(E) = 10

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
st[]	P	M			A	C	S	H	L		E				R	X

M = 16

Linear probing hash table

Hash. Map key to integer i between 0 and $M - 1$.
Insert. Put at table index i if free; if not try $i + 1$, $i + 2$, etc.
Search. Search table index i; if occupied but no match, try $i + 1$, $i + 2$, etc.

search E
hash(E) = 10

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
st[]	P	M			A	C	S	H	L		E				R	X
M = 16											E					

search hit
(return corresponding value)

Linear probing hash table

Hash. Map key to integer i between 0 and $M - 1$.
Insert. Put at table index i if free; if not try $i + 1$, $i + 2$, etc.
Search. Search table index i; if occupied but no match, try $i + 1$, $i + 2$, etc.

linear probing hash table

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
st[]	P	M			A	C	S	H	L		E				R	X

M = 16

Linear probing hash table

Hash. Map key to integer i between 0 and $M - 1$.
Insert. Put at table index i if free; if not try $i + 1$, $i + 2$, etc.
Search. Search table index i; if occupied but no match, try $i + 1$, $i + 2$, etc.

search L
hash(L) = 6

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
st[]	P	M			A	C	S	H	L		E				R	X

M = 16

Linear probing hash table

Hash. Map key to integer i between 0 and $M - 1$.
Insert. Put at table index i if free; if not try $i + 1$, $i + 2$, etc.
Search. Search table index i; if occupied but no match, try $i + 1$, $i + 2$, etc.

search L
hash(L) = 6

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
st[]	P	M			A	C	S	H	L		E				R	X
M = 16							L									

Linear probing hash table

Hash. Map key to integer i between 0 and $M - 1$.
Insert. Put at table index i if free; if not try $i + 1$, $i + 2$, etc.
Search. Search table index i; if occupied but no match, try $i + 1$, $i + 2$, etc.

search L
hash(L) = 6

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
st[]	P	M			A	C	S	H	L		E				R	X
								L								

M = 16

Linear probing hash table

Hash. Map key to integer i between 0 and $M - 1$.
Insert. Put at table index i if free; if not try $i + 1$, $i + 2$, etc.
Search. Search table index i; if occupied but no match, try $i + 1$, $i + 2$, etc.

search L
hash(L) = 6

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
st[]	P	M			A	C	S	H	L		E				R	X
									L							

M = 16

search hit
(return corresponding value)

Linear probing hash table

Hash. Map key to integer i between 0 and $M - 1$.
Insert. Put at table index i if free; if not try $i + 1$, $i + 2$, etc.
Search. Search table index i; if occupied but no match, try $i + 1$, $i + 2$, etc.

linear probing hash table

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
st[]	P	M			A	C	S	H	L		E				R	X

M = 16

Linear probing hash table

Hash. Map key to integer i between 0 and $M - 1$.
Insert. Put at table index i if free; if not try $i + 1$, $i + 2$, etc.
Search. Search table index i; if occupied but no match, try $i + 1$, $i + 2$, etc.

search K
hash(K) = 5

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
st[]	P	M			A	C	S	H	L		E				R	X

M = 16

Linear probing hash table

Hash. Map key to integer i between 0 and $M-1$.

Insert. Put at table index i if free; if not try $i+1$, $i+2$, etc.

Search. Search table index i; if occupied but no match, try $i+1$, $i+2$, etc.

search K
hash(K) = 5

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
st[]	P	M			A	C	S	H	L		E				R	X
						K										

M = 16

Linear probing hash table

Hash. Map key to integer i between 0 and $M-1$.

Insert. Put at table index i if free; if not try $i+1$, $i+2$, etc.

Search. Search table index i; if occupied but no match, try $i+1$, $i+2$, etc.

search K
hash(K) = 5

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
st[]	P	M			A	C	S	H	L		E				R	X
							K									

M = 16

Linear probing hash table

Hash. Map key to integer i between 0 and $M-1$.

Insert. Put at table index i if free; if not try $i+1$, $i+2$, etc.

Search. Search table index i; if occupied but no match, try $i+1$, $i+2$, etc.

search K
hash(K) = 5

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
st[]	P	M			A	C	S	H	L		E				R	X
								K								

M = 16

Linear probing hash table

Hash. Map key to integer i between 0 and $M-1$.

Insert. Put at table index i if free; if not try $i+1$, $i+2$, etc.

Search. Search table index i; if occupied but no match, try $i+1$, $i+2$, etc.

search K
hash(K) = 5

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
st[]	P	M			A	C	S	H	L		E				R	X
									K							

M = 16

Linear probing hash table

Hash. Map key to integer i between 0 and $M - 1$.
Insert. Put at table index i if free; if not try $i + 1$, $i + 2$, etc.
Search. Search table index i; if occupied but no match, try $i + 1$, $i + 2$, etc.

search K
hash(K) = 5

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
st[]	P	M			A	C	S	H	L		E				R	X
										K						

M = 16

search miss
(return null)

Linear probing - Summary

Hash. Map key to integer i between 0 and $M - 1$.
Insert. Put at table index i if free; if not try $i + 1$, $i + 2$, etc.
Search. Search table index i; if occupied but no match, try $i + 1$, $i + 2$, etc.

Note. Array size M must be greater than number of key-value pairs N.

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
st[]	P	M			A	C	S	H	L		E				R	X

M = 16

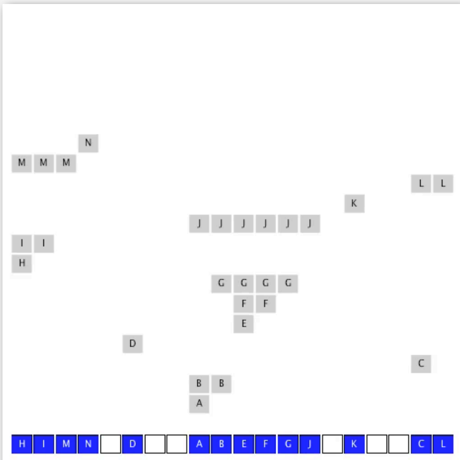
Linear probing ST implementation

```
public class LinearProbingHashST<Key, Value>
{
   private int M = 30001;
   private Value[] vals = (Value[]) new Object[M];
   private Key[]   keys = (Key[])   new Object[M];

   private int hash(Key key) {  /* as before */  }

   public void put(Key key, Value val)
   {
      int i;
      for (i = hash(key); keys[i] != null; i = (i+1) % M)
         if (keys[i].equals(key))
             break;
      keys[i] = key;
      vals[i] = val;
   }

   public Value get(Key key)
   {
      for (int i = hash(key); keys[i] != null; i = (i+1) % M)
         if (key.equals(keys[i]))
             return vals[i];
      return null;
   }
}
```

array doubling and halving code omitted

Clustering

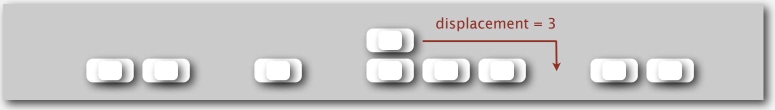
Cluster. A contiguous block of items.
Observation. New keys likely to hash into middle of big clusters.



Knuth's parking problem

Model. Cars arrive at one-way street with M parking spaces. Each desires a random space i : if space i is taken, try $i+1$, $i+2$, etc.

Q. What is mean displacement of a car?



Half-full. With $M/2$ cars, mean displacement is $\sim 3/2$.

Full. With M cars, mean displacement is $\sim \sqrt{\pi M/8}$

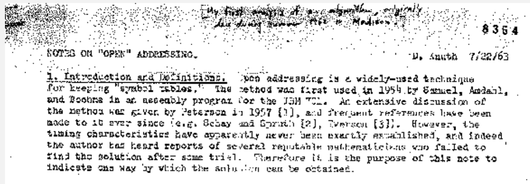
Analysis of linear probing

Proposition. Under uniform hashing assumption, the average number of probes in a linear probing hash table of size M that contains $N = \alpha M$ keys is:

$$\sim \frac{1}{2}\left(1 + \frac{1}{1-\alpha}\right) \qquad \sim \frac{1}{2}\left(1 + \frac{1}{(1-\alpha)^2}\right)$$

search hit — search miss / insert

Pf.



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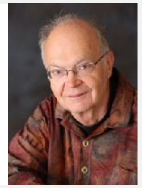
NOTES ON "OPEN" ADDRESSING. D. Knuth 7/22/63

1. Introduction and Definitions. Open addressing is a widely-used technique for keeping "symbol tables." The method was first used in 1954 by Samuel, Amdahl, and Boehme in an assembly program for the IBM 701. An extensive discussion of the method was given by Peterson in 1957 [1], and frequent references have been made to it ever since (e.g. Schay and Spruth [2], Iverson [3]). However, the timing characteristics have apparently never been exactly established, and indeed the author has heard reports of several reputable mathematicians who failed to find the solution after some trial. Therefore it is the purpose of this note to indicate one way by which the solution can be obtained.



Parameters.

- M too large $\Rightarrow$ too many empty array entries.
- M too small $\Rightarrow$ search time blows up.
- Typical choice: $\alpha = N/M \sim ½$. ← # probes for search hit is about 3/2; # probes for search miss is about 5/2

ST implementations: summary

implementation	worst-case cost (after N inserts)			average case (after N random inserts)			ordered iteration?	key interface
	search	insert	delete	search hit	insert	delete		
sequential search (unordered list)	N	N	N	N/2	N	N/2	no	`equals()`
binary search (ordered array)	lg N	N	N	lg N	N/2	N/2	yes	`compareTo()`
BST	N	N	N	1.38 lg N	1.38 lg N	?	yes	`compareTo()`
red-black tree	2 lg N	2 lg N	2 lg N	1.00 lg N	1.00 lg N	1.00 lg N	yes	`compareTo()`
separate chaining	N *	N *	N *	3-5 *	3-5 *	3-5 *	no	`equals()`
linear probing	N *	N *	N *	3-5 *	3-5 *	3-5 *	no	`equals()`

* under uniform hashing assumption

War story: String hashing in Java

String `hashCode()` in Java 1.1.

- For long strings: only examine 8-9 evenly spaced characters.
- Benefit: saves time in performing arithmetic.

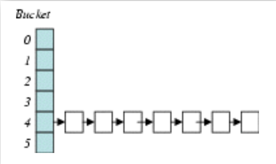
```
public int hashCode()
{
   int hash = 0;
   int skip = Math.max(1, length() / 8);
   for (int i = 0; i < length(); i += skip)
      hash = s[i] + (37 * hash);
   return hash;
}
```

- Downside: great potential for bad collision patterns.

```
http://www.cs.princeton.edu/introcs/13loop/Hello.java
http://www.cs.princeton.edu/introcs/13loop/Hello.class
http://www.cs.princeton.edu/introcs/13loop/Hello.html
http://www.cs.princeton.edu/introcs/12type/index.html
↑      ↑      ↑      ↑      ↑      ↑      ↑      ↑
```

War story: algorithmic complexity attacks

Q. Is the uniform hashing assumption important in practice?
A. Obvious situations: aircraft control, nuclear reactor, pacemaker.
A. Surprising situations: denial-of-service attacks.



malicious adversary learns your hash function (e.g., by reading Java API) and causes a big pile-up in single slot that grinds performance to a halt

Real-world exploits. [Crosby-Wallach 2003]

- Bro server: send carefully chosen packets to DOS the server, using less bandwidth than a dial-up modem.
- Perl 5.8.0: insert carefully chosen strings into associative array.
- Linux 2.4.20 kernel: save files with carefully chosen names.

Algorithmic complexity attack on Java

Goal. Find family of strings with the same hash code.
Solution. The base 31 hash code is part of Java's string API.

key	hashCode()
"Aa"	2112
"BB"	2112

key	hashCode()
"AaAaAaAa"	-540425984
"AaAaAaBB"	-540425984
"AaAaBBAa"	-540425984
"AaAaBBBB"	-540425984
"AaBBAaAa"	-540425984
"AaBBAaBB"	-540425984
"AaBBBBAa"	-540425984
"AaBBBBBB"	-540425984

key	hashCode()
"BBAaAaAa"	-540425984
"BBAaAaBB"	-540425984
"BBAaBBAa"	-540425984
"BBAaBBBB"	-540425984
"BBBBAaAa"	-540425984
"BBBBAaBB"	-540425984
"BBBBBBAa"	-540425984
"BBBBBBBB"	-540425984

2^N strings of length 2N that hash to same value!

Diversion: one-way hash functions

One-way hash function. "Hard" to find a key that will hash to a desired value (or two keys that hash to same value).

Ex. MD4, MD5, SHA-0, SHA-1, SHA-2, WHIRLPOOL, RIPEMD-160, ….

known to be insecure

```
String password = args[0];
MessageDigest sha1 =
MessageDigest.getInstance("SHA1");
byte[] bytes = sha1.digest(password);

/* prints bytes as hex string */
```

Applications. Digital fingerprint, message digest, storing passwords.
Caveat. Too expensive for use in ST implementations.

Separate chaining vs. linear probing

Separate chaining.

- Easier to implement delete.
- Performance degrades gracefully.
- Clustering less sensitive to poorly-designed hash function.

Linear probing.

- Less wasted space.
- Better cache performance.

Q. How to delete?
Q. How to resize?

Hashing: variations on the theme

Many improved versions have been studied.

Two-probe hashing. (separate-chaining variant)

- Hash to two positions, insert key in shorter of the two chains.
- Reduces expected length of the longest chain to $\log \log N$.

Double hashing. (linear-probing variant)

- Use linear probing, but skip a variable amount, not just 1 each time.
- Effectively eliminates clustering.
- Can allow table to become nearly full.
- More difficult to implement delete.

Cuckoo hashing. (linear-probing variant)

- Hash key to two positions; insert key into either position; if occupied, reinsert displaced key into its alternative position (and recur).
- Constant worst case time for search.

Hash tables vs. balanced search trees

Hash tables.

- Simpler to code.
- No effective alternative for unordered keys.
- Faster for simple keys (a few arithmetic ops versus $\log N$ compares).
- Better system support in Java for strings (e.g., cached hash code).

Balanced search trees.

- Stronger performance guarantee.
- Support for ordered ST operations.
- Easier to implement `compareTo()` correctly than `equals()` and `hashCode()`.

Java system includes both.

- Red-black BSTs: `java.util.TreeMap`, `java.util.TreeSet`.
- Hash tables: `java.util.HashMap`, `java.util.IdentityHashMap`.

TODAY

- Hashing
- Search applications

SEARCH APPLICATIONS

- Sets
- Dictionary clients
- Indexing clients
- Sparse vectors

Set API

Mathematical set. A collection of distinct keys.

```
public class SET<Key extends Comparable<Key>>
```

	`SET()`	*create an empty set*
`void`	`add(Key key)`	*add the key to the set*
`boolean`	`contains(Key key)`	*is the key in the set?*
`void`	`remove(Key key)`	*remove the key from the set*
`int`	`size()`	*return the number of keys in the set*
`Iterator<Key>`	`iterator()`	*iterator through keys in the set*

Q. How to implement?

A. Remove "value" from any ST implementation

Exception filter

- Read in a list of words from one file.
- Print out all words from standard input that are { in, not in } the list.

```
% more list.txt
was it the of

% java WhiteList list.txt < tinyTale.txt
it was the of it was the of
it was the of it was the of
it was the of it was the of
it was the of it was the of
it was the of it was the of

% java BlackList list.txt < tinyTale.txt
best times worst times
age wisdom age foolishness
epoch belief epoch incredulity
season light season darkness
spring hope winter despair
```

list of exceptional words

Exception filter applications

- Read in a list of words from one file.
- Print out all words from standard input that are { in, not in } the list.

application	purpose	key	in list
spell checker	identify misspelled words	word	dictionary words
browser	mark visited pages	URL	visited pages
parental controls	block sites	URL	bad sites
chess	detect draw	board	positions
spam filter	eliminate spam	IP address	spam addresses
credit cards	check for stolen cards	number	stolen cards

Exception filter: Java implementation

- Read in a list of words from one file.
- Print out all words from standard input that are { in, not in } the list.

```
public class WhiteList
{
   public static void main(String[] args)
   {
      SET<String> set = new SET<String>();

      In in = new In(args[0]);
      while (!in.isEmpty())
         set.add(in.readString());

      while (!StdIn.isEmpty())
      {
         String word = StdIn.readString();
         if (set.contains(word))
            StdOut.println(word);
      }
   }
}
```

create empty set of strings

read in whitelist

print words not in list

Exception filter: Java implementation

- Read in a list of words from one file.
- Print out all words from standard input that are { in, not in } the list.

```
public class BlackList
{
   public static void main(String[] args)
   {
      SET<String> set = new SET<String>();

      In in = new In(args[0]);
      while (!in.isEmpty())
         set.add(in.readString());

      while (!StdIn.isEmpty())
      {
         String word = StdIn.readString();
         if (!set.contains(word))
            StdOut.println(word);
      }
   }
}
```

create empty set of strings

read in whitelist

print words not in list

SEARCH APPLICATIONS

Dictionary lookup

Command-line arguments.

- A comma-separated value (CSV) file.
- Key field.
- Value field.

Ex 1. DNS lookup.

URL is key — IP is value

```
% java LookupCSV ip.csv 0 1
adobe.com
192.150.18.60
www.princeton.edu
128.112.128.15
ebay.edu
Not found
```

IP is key — URL is value

```
% java LookupCSV ip.csv 1 0
128.112.128.15
www.princeton.edu
999.999.999.99
Not found
```

```
% more ip.csv
www.princeton.edu,128.112.128.15
www.cs.princeton.edu,128.112.136.35
www.math.princeton.edu,128.112.18.11
www.cs.harvard.edu,140.247.50.127
www.harvard.edu,128.103.60.24
www.yale.edu,130.132.51.8
www.econ.yale.edu,128.36.236.74
www.cs.yale.edu,128.36.229.30
espn.com,199.181.135.201
yahoo.com,66.94.234.13
msn.com,207.68.172.246
google.com,64.233.167.99
baidu.com,202.108.22.33
yahoo.co.jp,202.93.91.141
sina.com.cn,202.108.33.32
ebay.com,66.135.192.87
adobe.com,192.150.18.60
163.com,220.181.29.154
passport.net,65.54.179.226
tom.com,61.135.158.237
nate.com,203.226.253.11
cnn.com,64.236.16.20
daum.net,211.115.77.211
blogger.com,66.102.15.100
fastclick.com,205.180.86.4
wikipedia.org,66.230.200.100
rakuten.co.jp,202.72.51.22
...
```


Dictionary lookup

Command-line arguments.

- A comma-separated value (CSV) file.
- Key field.
- Value field.

Ex 2. Amino acids.

codon is key — name is value

```
% java LookupCSV amino.csv 0 3
ACT
Threonine
TAG
Stop
CAT
Histidine
```

```
% more amino.csv
TTT,Phe,F,Phenylalanine
TTC,Phe,F,Phenylalanine
TTA,Leu,L,Leucine
TTG,Leu,L,Leucine
TCT,Ser,S,Serine
TCC,Ser,S,Serine
TCA,Ser,S,Serine
TCG,Ser,S,Serine
TAT,Tyr,Y,Tyrosine
TAC,Tyr,Y,Tyrosine
TAA,Stop,Stop,Stop
TAG,Stop,Stop,Stop
TGT,Cys,C,Cysteine
TGC,Cys,C,Cysteine
TGA,Stop,Stop,Stop
TGG,Trp,W,Tryptophan
CTT,Leu,L,Leucine
CTC,Leu,L,Leucine
CTA,Leu,L,Leucine
CTG,Leu,L,Leucine
CCT,Pro,P,Proline
CCC,Pro,P,Proline
CCA,Pro,P,Proline
CCG,Pro,P,Proline
CAT,His,H,Histidine
CAC,His,H,Histidine
CAA,Gln,Q,Glutamine
CAG,Gln,Q,Glutamine
CGT,Arg,R,Arginine
CGC,Arg,R,Arginine
...
```

Dictionary lookup

Command-line arguments.

- A comma-separated value (CSV) file.
- Key field.
- Value field.

Ex 3. Class list.

```
% java LookupCSV classlist.csv 4 1
eberl
Ethan
nwebb
Natalie

% java LookupCSV classlist.csv 4 3
dpan
P01
```

login is key, first name is value (arguments 4 1)

login is key, precept is value (arguments 4 3)

```
% more classlist.csv
13,Berl,Ethan Michael,P01,eberl
11,Bourque,Alexander Joseph,P01,abourque
12,Cao,Phillips Minghua,P01,pcao
11,Chehoud,Christel,P01,cchehoud
10,Douglas,Malia Morioka,P01,malia
12,Haddock,Sara Lynn,P01,shaddock
12,Hantman,Nicole Samantha,P01,nhantman
11,Hesterberg,Adam Classen,P01,ahesterb
13,Hwang,Roland Lee,P01,rhwang
13,Hyde,Gregory Thomas,P01,ghyde
13,Kim,Hyunmoon,P01,hktwo
11,Kleinfeld,Ivan Maximillian,P01,ikleinfe
12,Korac,Damjan,P01,dkorac
11,MacDonald,Graham David,P01,gmacdona
10,Michal,Brian Thomas,P01,bmichal
12,Nam,Seung Hyeon,P01,seungnam
11,Nastasescu,Maria Monica,P01,mnastase
11,Pan,Di,P01,dpan
12,Partridge,Brenton Alan,P01,bpartrid
13,Rilee,Alexander,P01,arilee
13,Roopakalu,Ajay,P01,aroopaka
11,Sheng,Ben C,P01,bsheng
12,Webb,Natalie Sue,P01,nwebb
...
```


Dictionary lookup: Java implementation

```
public class LookupCSV
{
   public static void main(String[] args)
   {
      In in = new In(args[0]);
      int keyField = Integer.parseInt(args[1]);
      int valField = Integer.parseInt(args[2]);

      ST<String, String> st = new ST<String, String>();
      while (!in.isEmpty())
      {
         String line = in.readLine();
         String[] tokens = database[i].split(",");
         String key = tokens[keyField];
         String val = tokens[valField];
         st.put(key, val);
      }

      while (!StdIn.isEmpty())
      {
         String s = StdIn.readString();
         if (!st.contains(s)) StdOut.println("Not found");
         else                 StdOut.println(st.get(s));
      }
   }
}
```

process input file

build symbol table

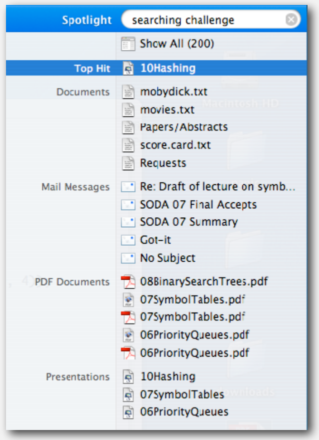
process lookups with standard I/O

Search Applications

- Sets
- Dictionary clients
- **Indexing clients**
- Sparse vectors

File indexing

Goal. Index a PC (or the web).



File indexing

Goal. Given a list of files specified, create an index so that you can efficiently find all files containing a given query string.

```
% ls *.txt
aesop.txt magna.txt moby.txt
sawyer.txt tale.txt

% java FileIndex *.txt
freedom
magna.txt moby.txt tale.txt

whale
moby.txt

lamb
sawyer.txt aesop.txt
```

```
% ls *.java

% java FileIndex *.java
BlackList.java Concordance.java
DeDup.java FileIndex.java ST.java
SET.java WhiteList.java

import
FileIndex.java SET.java ST.java

Comparator
null
```


File indexing

Goal. Given a list of files specified, create an index so that you can efficiently find all files containing a given query string.

```
% ls *.txt
aesop.txt magna.txt moby.txt
sawyer.txt tale.txt

% java FileIndex *.txt
freedom
magna.txt moby.txt tale.txt

whale
moby.txt

lamb
sawyer.txt aesop.txt
```

```
% ls *.java

% java FileIndex *.java
BlackList.java Concordance.java
DeDup.java FileIndex.java ST.java
SET.java WhiteList.java

import
FileIndex.java SET.java ST.java

Comparator
null
```


Solution. Key = query string; value = set of files containing that string.

File indexing

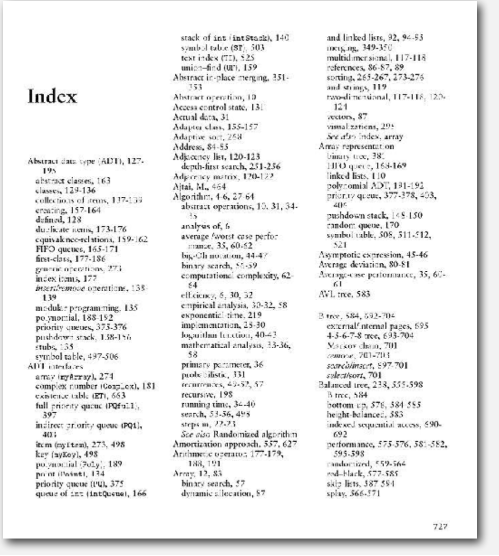
```
public class FileIndex
{
   public static void main(String[] args)
   {
      ST<String, SET<File>> st = new ST<String, SET<File>>();   // symbol table

      for (String filename : args) {                            // list of file names from command line
         File file = new File(filename);
         In in = new In(file);
         while !(in.isEmpty())
         {
            String word = in.readString();                      // for each word in file, add file to corresponding set
            if (!st.contains(word))
               st.put(s, new SET<File>());
            SET<File> set = st.get(key);
            set.add(file);
         }
      }

      while (!StdIn.isEmpty())
      {
         String query = StdIn.readString();                     // process queries
         StdOut.println(st.get(query));
      }
   }
}
```


Book index

Goal. Index for an e-book.



Concordance

Goal. Preprocess a text corpus to support concordance queries: given a word, find all occurrences with their immediate contexts.

```
% java Concordance tale.txt
cities
tongues of the two *cities* that were blended in

majesty
their turnkeys and the *majesty* of the law fired
me treason against the *majesty* of the people in
of his most gracious *majesty* king george the third

princeton
no matches
```


Concordance

```
public class Concordance
{
   public static void main(String[] args)
   {
      In in = new In(args[0]);
      String[] words = StdIn.readAll().split("\\s+");
      ST<String, SET<Integer>> st = new ST<String, SET<Integer>>();
      for (int i = 0; i < words.length; i++)
      {
         String s = words[i];
         if (!st.contains(s))
            st.put(s, new SET<Integer>());
         SET<Integer> pages = st.get(s);
         set.put(i);
      }

      while (!StdIn.isEmpty())
      {
         String query = StdIn.readString();
         SET<Integer> set = st.get(query);
         for (int k : set)
         // print words[k-5] to words[k+5]
      }
   }
}
```

read text and build index

process queries and print concordances

Search Applications

- Sets
- Dictionary clients
- Indexing clients
- Sparse vectors

Vectors and matrices

Vector. Ordered sequence of N real numbers.

Matrix. N-by-N table of real numbers.

vector operations

$$a = [\,0 \;\; 3 \;\; 15\,], \quad b = [-1 \;\; 2 \;\; 2\,]$$
$$a + b = [-1 \;\; 5 \;\; 17\,]$$
$$a \circ b = (0 \cdot -1) + (3 \cdot 2) + (15 \cdot 2) = 36$$
$$|a| = \sqrt{a \circ a} = \sqrt{0^2 + 3^2 + 15^2} = 3\sqrt{26}$$

matrix-vector multiplication

$$\begin{bmatrix} 0 & 1 & 1 \\ 2 & 4 & -2 \\ 0 & 3 & 15 \end{bmatrix} \times \begin{bmatrix} -1 \\ 2 \\ 2 \end{bmatrix} = \begin{bmatrix} 4 \\ 2 \\ 36 \end{bmatrix}$$

Sparse vectors and matrices

Sparse vector. An N-dimensional vector is sparse if it contains O(1) nonzeros.
Sparse matrix. An N-by-N matrix is sparse if it contains O(N) nonzeros.

Property. Large matrices that arise in practice are sparse.

$$\begin{bmatrix} 0 & 0 & .36 & .36 & .18 \end{bmatrix}$$

$$\begin{bmatrix} 0 & .90 & 0 & 0 & 0 \\ 0 & 0 & .36 & .36 & .18 \\ 0 & 0 & 0 & .90 & 0 \\ .90 & 0 & 0 & 0 & 0 \\ .47 & 0 & .47 & 0 & 0 \end{bmatrix}$$

Matrix-vector multiplication (standard implementation)

a[][] x[] b[]

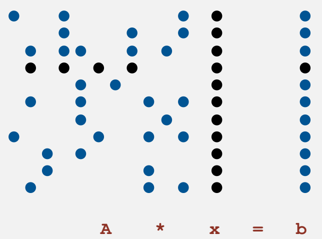
$$\begin{bmatrix} 0 & .90 & 0 & 0 & 0 \\ 0 & 0 & .36 & .36 & .18 \\ 0 & 0 & 0 & .90 & 0 \\ .90 & 0 & 0 & 0 & 0 \\ .47 & 0 & .47 & 0 & 0 \end{bmatrix} \begin{bmatrix} .05 \\ .04 \\ .36 \\ .37 \\ .19 \end{bmatrix} = \begin{bmatrix} .036 \\ .297 \\ .333 \\ .045 \\ .1927 \end{bmatrix}$$

```
...
double[][] a = new double[N][N];
double[] x = new double[N];
double[] b = new double[N];
...
// initialize a[][] and x[]
...
for (int i = 0; i < N; i++)
{
   sum = 0.0;
   for (int j = 0; j < N; j++)
      sum += a[i][j]*x[j];
   b[i] = sum;
}
```

nested loops (N^2 running time)

Sparse matrix-vector multiplication

Problem. Sparse matrix-vector multiplication.
Assumptions. Matrix dimension is 10,000; average nonzeros per row ~ 10.



Vector representations

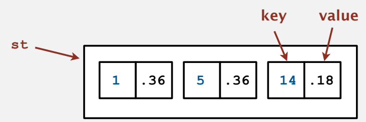
1D array (standard) representation.

- Constant time access to elements.
- Space proportional to N.

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
0	.36	0	0	0	.36	0	0	0	0	0	0	0	0	.18	0	0	0	0	0

Symbol table representation.

- Key = index, value = entry.
- Efficient iterator.
- Space proportional to number of nonzeros.



Sparse vector data type

```
public class SparseVector
{
   private HashST<Integer, Double> v;

   public SparseVector()
   {  v = new HashST<Integer, Double>();  }

   public void put(int i, double x)
   {  v.put(i, x);  }

   public double get(int i)
   {
      if (!v.contains(i)) return 0.0;
      else return v.get(i);
   }

   public Iterable<Integer> indices()
   {  return v.keys();  }

   public double dot(double[] that)
   {
       double sum = 0.0;
       for (int i : indices())
           sum += that[i]*this.get(i);
       return sum;
   }
}
```

- HashST because order not important
- empty ST represents all 0s vector
- a[i] = value
- return a[i]
- dot product is constant time for sparse vectors

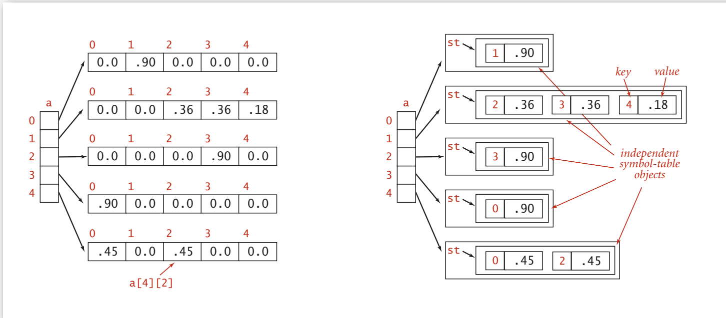
Matrix representations

2D array (standard) matrix representation: Each row of matrix is an array.

- Constant time access to elements.
- Space proportional to N^2.

Sparse matrix representation: Each row of matrix is a sparse vector.

- Efficient access to elements.
- Space proportional to number of nonzeros (plus N).



Sparse matrix-vector multiplication

$$
\underbrace{\begin{bmatrix} 0 & .90 & 0 & 0 & 0 \\ 0 & 0 & .36 & .36 & .18 \\ 0 & 0 & 0 & .90 & 0 \\ .90 & 0 & 0 & 0 & 0 \\ .47 & 0 & .47 & 0 & 0 \end{bmatrix}}_{a[][]}
\underbrace{\begin{bmatrix} .05 \\ .04 \\ .36 \\ .37 \\ .19 \end{bmatrix}}_{x[]}
=
\underbrace{\begin{bmatrix} .036 \\ .297 \\ .333 \\ .045 \\ .1927 \end{bmatrix}}_{b[]}
$$

```
..
SparseVector[] a = new SparseVector[N];
double[] x = new double[N];
double[] b = new double[N];
...
// Initialize a[] and x[]
...
for (int i = 0; i < N; i++)
   b[i] = a[i].dot(x);
```

linear running time for sparse matrix

Sample searching challenge

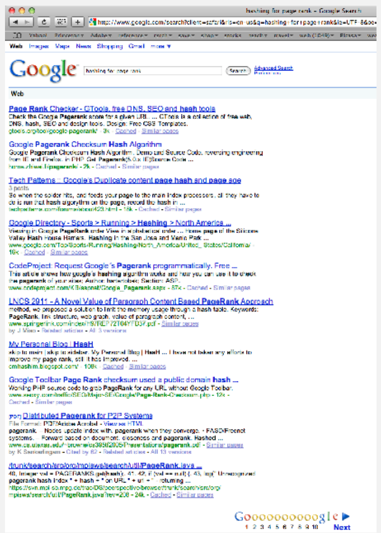
Problem. Rank pages on the web.

Assumptions.

- Matrix-vector multiply
- 10 billion+ rows
- sparse

Which "searching" method to use to access array values?

1. Standard 2D array representation
2. Symbol table
3. Doesn't matter much.

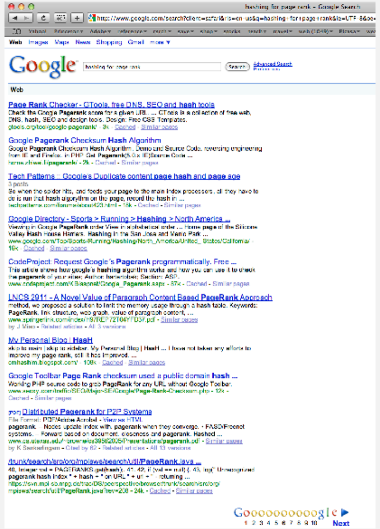


Sample searching challenge

Problem. Rank pages on the web.

Assumptions.

- Matrix-vector multiply
- 10 billion+ rows
- sparse



Which "searching" method to use to access array values?

~~1. Standard 2D array representation~~

✓ 2. Symbol table

~~3. Doesn't matter much.~~

cannot be done without fast algorithm

Sparse vector data type

```
public class SparseVector
{
   private int N;                        // length
   private ST<Integer, Double> st;       // the elements

   public SparseVector(int N)
   {
      this.N  = N;
      this.st = new ST<Integer, Double>();
   }

   public void put(int i, double value)
   {
      if (value == 0.0) st.remove(i);
      else              st.put(i, value);
   }

   public double get(int i)
   {
      if (st.contains(i)) return st.get(i);
      else                return 0.0;
   }

   ...
```

- all 0s vector
- a[i] = value
- return a[i]

Sparse vector data type (cont)

```
   public double dot(SparseVector that)
   {
      double sum = 0.0;
      for (int i : this.st)
         if (that.st.contains(i))
            sum += this.get(i) * that.get(i);
      return sum;
   }

   public double norm()
   {  return Math.sqrt(this.dot(this));  }

   public SparseVector plus(SparseVector that)
   {
      SparseVector c = new SparseVector(N);
      for (int i : this.st)
         c.put(i, this.get(i));
      for (int i : that.st)
         c.put(i, that.get(i) + c.get(i));
      return c;
   }

}
```

- dot product
- 2-norm
- vector sum

Sparse matrix data type

```
public class SparseMatrix
{
   private final int N;           // length
   private SparseVector[] rows;   // the elements

   public SparseMatrix(int N)
   {
      this.N  = N;
      this.rows = new SparseVector[N];
      for (int i = 0; i < N; i++)
         this.rows[i] = new SparseVector(N);
   }

   public void put(int i, int j, double value)
   {  rows[i].put(j, value);  }

   public double get(int i, int j)
   {  return rows[i].get(j);  }

   public SparseVector times(SparseVector x)
   {
      SparseVector b = new SparseVector(N);
      for (int i = 0; i < N; i++)
         b.put(i, rows[i].dot(x));
      return b;
   }
}
```

- all 0s matrix
- a[i][j] = value
- return a[i][j]
- matrix-vector multiplication

Compressed row storage (CRS)

Compressed row storage.

- Store nonzeros in a 1D array `val[]`.
- Store column index of each nonzero in parallel 1D array `col[]`.
- Store first index of each row in array `row[]`.

$$A = \begin{bmatrix} 11 & 0 & 0 & 41 \\ 0 & 22 & 0 & 0 \\ 0 & 0 & 33 & 43 \\ 14 & 0 & 34 & 44 \\ 0 & 25 & 0 & 0 \\ 16 & 26 & 36 & 46 \end{bmatrix}$$

i	row[]
0	0
1	2
2	3
3	5
4	8
5	9
6	13

i	col[]	val[]
0	1	11
1	4	41
2	2	22
3	3	33
4	4	43
5	1	14
6	3	34
7	4	44
8	2	25
9	1	16
10	2	26
11	3	36
12	4	46

Compressed row storage (CRS)

Benefits.

- Cache-friendly.
- Space proportional to number of nonzeros.
- Very efficient matrix-vector multiply.

```
double[] y = new double[N];
for (int i = 0; i < n; i++)
    for (int j = row[i]; j < row[i+1]; j++)
        y[i] += val[j] * x[col[j]];
```

Downside. No easy way to add/remove nonzeros.

Applications. Sparse Matlab.