This material takes 1:05.

Hashing

Dictionaries

- Operations.
    - makeset, insert, delete, find

Model

- keys are integers in $M = \{1, \ldots, m\}$
- (so assume machine word size, or "unit time," is $\log m$)
- can store in array of size M
- using power: arithmetic, indirect addressing
- compare to comparison and pointer based sorting, binary trees
- problem: space.

Hashing:

- find function h mapping M into table of size $n \ll m$
- Note some items get mapped to same place: "collision"
- use linked list etc.
- search, insert cost equals size of linked list
- goal: keep linked lists small: few collisions

Hash families:

- problem: for any hash function, some bad input (if n items, then m/n items to same bucket)
- This true even if hash is e.g. SHA1
- Solution: build family of functions, choose one that works well

Set of all functions?

- Idea: choose "function" that stores items in sorted order without collisions
- problem: to evaluate function, must examine all data
- evaluation time $\Omega(\log n)$.

- "description size" $\Omega(n \log m)$,
- Better goal: choose function that can be evaluated in constant time without looking at data (except query key)

How about a random function?

- set S of s items
- If $s = n$, balls in bins
  - $O((\log n)/(\log \log n))$ collisions w.h.p.
  - And matches that somewhere
  - but we care more about *average* collisions over many operations
  - $C_{ij} = 1$ if i, j collide
  - Time to find i is $\sum_j C_{ij}$
  - expected value $(n-1)/n \leq 1$
- more generally expected search time for item (present or not): $O(s/n) = O(1)$ if $s = n$

Problem:

- n^m functions (specify one of n places for each of n items)
  - too much space to specify $(m \log n)$,
  - hard to evaluate
- for $O(1)$ search time, need to identify function in $O(1)$ time.
  - so function description must fit in $O(1)$ machine words
  - Assuming $\log m$ bit words
  - So, fixed number of cells can only distinguish poly(m) functions
- This bounds size of hash family we can choose from

Our analysis:

- sloppier constants
- but more intuitive than book

2-universal family: [Carter-Wegman]

- Key insight: don't need entirely random function
- All we care about is which pairs of items collide
- so: OK if items land *pairwise independent*

- pick p in range $m, \ldots, 2m$ (not random)
- pick random a, b
- map x to $(ax + b \bmod p) \bmod n$
  - pairwise independent, uniform before $\bmod n$
  - So pairwise independent, near-uniform after $\bmod n$
  - at most 2 "uniform buckets" to same place
- argument above holds: $O(1)$ expected search time.
- represent with two $O(\log m)$-bit integers: hash family of poly size.
- *max* load may be large is $\sqrt{n}$, but who cares?
  - expected load in a bin is 1
  - so $O(\sqrt{n})$ with prob. 1-1/n (chebyshev).
  - this bounds expected max-load
  - some item may have bad load, but unlikely to be the requested one
  - can show the max load is probably achieved for some 2-universal families

perfect hash families

Ideally, would hash with *no* collisions

- Explore case of fixed set of n items (read only)
- perfect hash function: no collisions
- Even fully random function of n to n has collisions

Alternative try: use more space:

- How big can s be for random s to n without collisions?
  - Expected number of collisions is $E[\sum C_{ij}] = \binom{s}{2}(1/n) \approx s^2/2n$
  - **Markov Inequality:** $s = \sqrt{n}$ works with prob. 1/2
  - Nonzero probability, so, 2-universal hashes can work in quadratic space.
- Is this best possible?
  - Birthday problem: $(1 - 1/n) \cdots (1 - s/n) \approx e^{-(1/n + 2/n + \cdots + s/n)} \approx e^{-s^2/2n}$
  - So, when $s = \sqrt{n}$ has $\Omega(1)$ chance of collision
  - 23 for birthdays
  - even for fully independent

Finding one

- We know one exists—how find it?
- Try till succeed
- Each time, succeed with probability 1/2
- Expected number of tries to succeed is 2
- Probability need k tries is 2^{-k}

Two level hashing for linear space

- Hash s items into $O(s)$ space 2-universally
- Build quadratic size hash table on contents of each bucket
- bound $\sum b_k^2 = \sum_k (\sum_i [i \in b_k])^2 = \sum C_i + C_{ij}$
- expected value $O(s)$.
- So try till get (markov)
- Then build collision-free quadratic tables inside
- Try till get
- Polynomial time in s, Las-vegas algorithm
- Easy: $6s$ cells
- Hard: $s + o(s)$ cells (bit fiddling)

Define las vegas, compare to monte carlo.
Derandomization

- Probability 1/2 top-level function works
- Only m^2 top-level functions
- Try them all!
- Polynomial in m (not n), deterministic algorithm