Week 06 Lecture

Assignment 1 Review

Add a new base data type to PostgreSQL

Email addresses: *local* **@** *domain*

Variable lengths, up to 128 chars, case-insensitive

Operators: **=** same, **>** greater (dom,loc), **~** same domain, etc.

Support btree index and hashed files

```
Local       ::= NamePart NameParts
Domain      ::= NamePart '.' NamePart NameParts
NamePart    ::= Letter | Letter NameChars (Letter|Digit)
NameParts   ::= Empty | '.' NamePart NameParts
NameChars   ::= Empty | (Letter|Digit|'-') NameChars
```

Need: storage structure, in/out/operator functions, operator classes

---

... Assignment 1 Review

Decisions for stored representation:

- split into local+domain or keep as one string
- canonicalize before storing or when using operators
- fixed-length structure or variable length structure

Typical solution:

```
struct Email { char local[128]; char domain[128]; }
```

Problems: wastes space, buffers too short (129 for `'\0'`)

Better solution:

```
struct Email { int32 len; int32 dom0; char addr[1]; }
```

Assumes: copy whole string, convert to lower-case, replace `'@'` by `'\0'`

... Assignment 1 Review

Storing in canonical form (e.g. all lower-case), and pre-split

- simplifies query-time operations like `email_cmp()`

Having a generic `email_cmp()` function

- simplifies rest of code, especially operator functions

Accesing data in var-length pre-split struct:

```
struct Email *ep;
ep = (struct Email *)PG_GETARG_POINTER(0);
char *local = &(ep->addr[0]);
char *domain = &(ep->addr[ep->dom0]);
```

... Assignment 1 Review

Common errors ...

- `struct Email { char *local; char *domain; }`
    - tuple data must be stored within the struct
- buffers of size 128 (should be 129, unless storing length)
- `sscanf(str, "[^@]@[^@]", locBuf, domBuf)`
- or even a regex like `"[A-Za-z0-9.-]+@[A-Za-z0-9.-]+"`
- `internallength = ?` in `create type EmailAddress`
    - needs to match `sizeof struct Email` (unless varlen)
- memory leaks (e.g. not freeing regex buffers)
- thinking that 20 tuples is going to use indexing

Debugging server errors can be tedious (`fprintf` to log file)

Recap on Implementing Selection

Selection = `select * from` *R* `where` *C*

- yields a subset of *R* tuples satisfying condition *C*
- a very important (frequent) operation in relational databases

Types of selection determined by type of condition

- *one*: `select * from` *R* `where id =` *k*
- *pmr*: `select * from` *R* `where age=65` (1-d)

  `select * from` *R* `where age=65 and gender='m'` (n-d)
- *rng*: `select * from` *R* `where age≥18 and age≤21` (1-d)

  `select * from` *R* `where age between 18 and 21` (n-d)
  `and height between 160 and 190`

... Recap on Implementing Selection

Strategies for implementing selection efficiently

- arrangement of tuples in file (e.g. sorting, hashing)
- auxiliary data structures (e.g. indexes, signatures)

Interested in cost for `select`, `delete`, `update`, and `insert`

- for `select`, simply count number of pages read n_r
- for others, use n_r and n_w to distinguish reads/writes

Typical file structure has

- *b* main data pages, b_{Ov} overflow pages, *c* tuples per page
- auxiliary files with e.g. oversized values, index entries

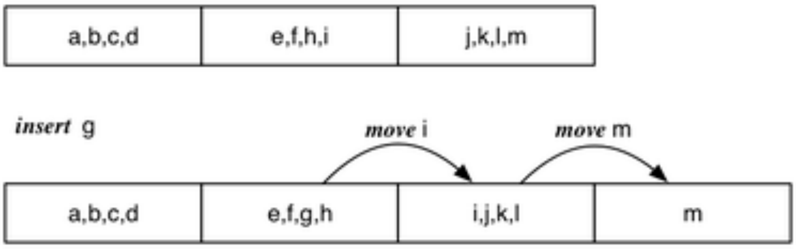
Sorted Files

Sorted Files

Records stored in file in order of some field *k* (the sort key).

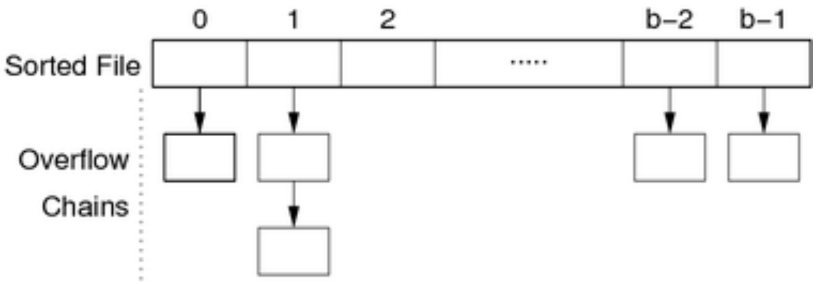
Makes searching more efficient; makes insertion less efficient

E.g. assume *c = 4*



... Sorted Files

In order to mitigate insertion costs, use overflow blocks.



Total number of overflow blocks = b_{ov}.

Average overflow chain length = $Ov = b_{ov} / b$.

Bucket = data page + its overflow page(s)

Selection in Sorted Files

For *one* queries on sort key, use binary search.

```
// select * from R where k = val  (sorted on R.k)
lo = 0; hi = b-1
while (lo <= hi) {
    mid = (lo+hi) div 2;
    (tup,loVal,hiVal) = searchBucket(f,mid,k,val);
    if (tup != null) return tup;
    else if (val < loVal) hi = mid - 1;
    else if (val > hiVal) lo = mid + 1;
    else return NOT_FOUND;
}
return NOT_FOUND;
```

where `f` is file for relation, `mid,lo,hi` are page indexes,
`k` is a field/attr, `val,loVal,hiVal` are values for `k`

... Selection in Sorted Files

Search a page and its overflow chain for a key value

```
searchBucket(f,p,k,val)
{
    buf = getPage(f,p);
    (tup,min,max) = searchPage(buf,k,val,+INF,-INF)
    if (tup != NULL) return(tup,min,max);
```

```
    ovf = openOvFile(f);
    ovp = ovflow(buf);
    while (tup == NULL && ovp != NO_PAGE) {
        buf = getPage(ovf,ovp);
        (tup,min,max) = searchPage(buf,k,val,min,max)
        ovp = ovflow(buf);
    }
    return (tup,min,max);
}
```

Assumes each page contains index of next page in Ov chain

... Selection in Sorted Files

Search within a page for key; also find min/max key values

```
searchPage(buf,k,val,min,max)
{
    res = NULL;
    for (i = 0; i < nTuples(buf); i++) {
        tup = getTuple(buf,i);
        if (tup.k == val) res = tup;
        if (tup.k < min) min = tup.k;
        if (tup.k > max) max = tup.k;
    }
    return (res,min,max);
}
```

... Selection in Sorted Files

The above method treats each bucket like a single large page.

Cases:

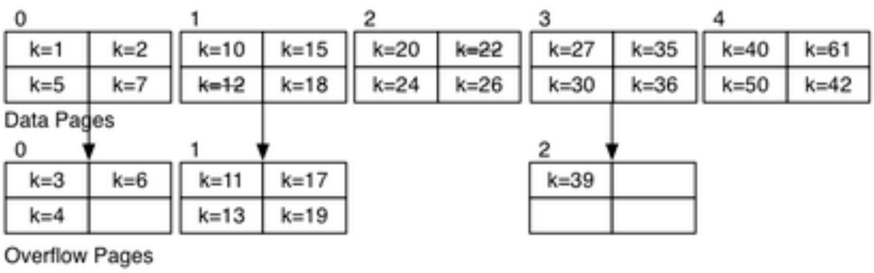
- best: find tuple in first data page we read
- worst: full binary search, and not found
    - examine $log_2 b$ data pages
    - plus examine all of their overflow pages
- average: examine some data pages + their overflow pages

$Cost_{one}$:   Best = *1*   Worst = $log_2\, b + b_{ov}$

Average case cost analysis relies on assumptions (e.g. data distribution)

Exercise 1: Searching in Sorted File

Consider this sorted file with overflows ($b=5$, $c=4$):



Compute the cost for answering each of the following:

- `select * from R where k = 24`

- `select * from R where k = 3`
- `select * from R where k = 14`
- `select max(k) from R`

Exercise 2: Optimising Sorted-file Search

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The `searchBucket(f,p,k,val)` function requires:

- read the p^{th} page from data file
- scan it to find a match and min/max k values in page
- while no match, repeat the above for each overflow page
- if we find a match in any page, return it
- otherwise, remember min/max over all pages in bucket

Suggest an optimisation that would improve `searchBucket()` performance for most buckets.

... Selection in Sorted Files

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For *pmr* query, on non-unique attribute *k*

- assume file is sorted on *k*
- tuples containing *k* may appear in several pages

Begin by locating a page *p* containing `k=`*val* (as for *one* query).

Scan backwards and forwards from *p* to find matches.

Thus, $Cost_{pmr} = Cost_{one} + (b_q\text{-}1).(1+Ov)$

... Selection in Sorted Files

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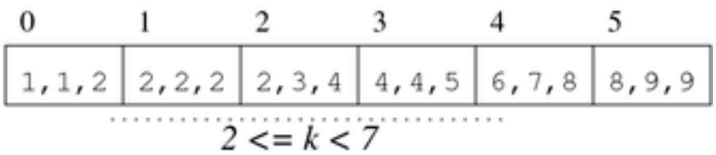
For *range* queries on unique sort key (e.g. primary key):

- use binary search to find lower bound
- read sequentially until reach upper bound

$Cost_{range} = Cost_{one} + (b_q\text{-}1).(1+Ov)$

If secondary key, similar method to *pmr*.



... Selection in Sorted Files

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So far, have assumed query condition involves sort key *k*.

If condition contains attribute *j*, not the sort key

- file is unlikely to be sorted by *j* as well
- sortedness gives no searching benefits

$Cost_{one}$, $Cost_{range}$, $Cost_{pmr}$ as for heap files

Updates to Sorted Files

Insertion approach:

- find appropriate page for tuple (via binary search)
- if page not full, insert into page
- otherwise, insert into next overflow block with space

Thus, $Cost_{insert} = Cost_{one} + \delta_w$ (where δ_w = 1 or 2)

Deletion strategy:

- find matching tuple(s)
- mark them as deleted

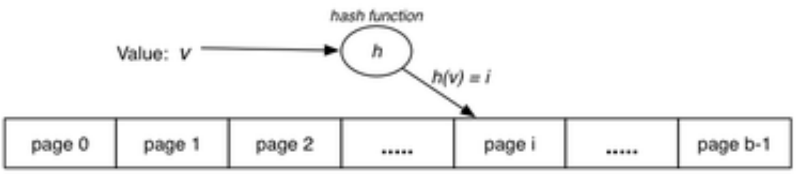
Cost depends on selectivity of selection condition

Thus, $Cost_{delete} = Cost_{select} + b_{qw}$

Hashed Files

Hashing

Basic idea: use key value to compute page address of tuple.



e.g. tuple with key = *v* is stored in page *i*

Requires: hash function *h(v)* that maps *KeyDomain* → *[0..b-1]*.

- hashing converts key value (any type) into integer value
- integer value is then mapped to page index
- note: can view integer value as a bit-string

... Hashing

PostgreSQL hash function (simplified):

```
uint32 hash_any(unsigned char *k, register int keylen)
{
   register uint32 a, b, c, len;
   /* Set up the internal state */
   len = keylen;   a = b = 0x9e3779b9;   c = 3923095;
   /* handle most of the key */
   while (len >= 12) {
      a += (k[0] + (k[1]<<8) + (k[2]<<16) + (k[3]<<24));
      b += (k[4] + (k[5]<<8) + (k[6]<<16) + (k[7]<<24));
      c += (k[8] + (k[9]<<8) + (k[10]<<16) + (k[11]<<24));
      mix(a, b, c);   k += 12; len -= 12;
```

```
    }
    /* collect any data from last 11 bytes into a,b,c */
    mix(a, b, c);
    return c;
}
```

See **backend/access/hash/hashfunc.c** for details (incl `mix()`)

... Hashing

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`hash_any()` gives hash value as 32-bit quantity (`uint32`).

Two ways to map raw hash value into a page address:

- if $b = 2^k$, bitwise AND with *k* low-order bits set to one

```
uint32 hashToPageNum(uint32 hval) {
    uint32 mask = 0xFFFFFFFF;
    return (hval & (mask >> (32-k)));
}
```

- otherwise, use *mod* to produce value in range *0..b-1*

```
uint32 hashToPageNum(uint32 hval) {
    return (hval % b);
}
```

Hashing Performance

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Aims:

- distribute tuples evenly amongst buckets
- have most buckets nearly full (attempt to minimise wasted space)

Note: if data distribution not uniform, address distribution can't be uniform.

Best case: every bucket contains same number of tuples.

Worst case: every tuple hashes to same bucket.

Average case: some buckets have more tuples than others.

Use overflow pages to handle "overfull" buckets (cf. sorted files)

All tuples in each bucket must have same hash value.

... Hashing Performance

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Two important measures for hash files:

- load factor: $L = r/bc$
- average overflow chain length: $Ov = b_{ov}/b$

Three cases for distribution of tuples in a hashed file:

Case	*L*	*Ov*
Best	≅ *1*	0
Worst	*>> 1*	**
Average	*< 1*	*0<Ov<1*

(** performance is same as Heap File)

To achieve average case, aim for $0.75 \le L \le 0.9$.

Selection with Hashing

Best performance occurs for *one* queries on hash key field.

Basic strategy:

- compute page address via hash function *hash(val)*
- fetch that page and look for matching tuple
- possibly fetch additional pages from overflow chain

Best $Cost_{one} = 1$ (find in data page)

Average $Cost_{one} = 1+Ov/2$ (scan half of ovflow chain)

Worst $Cost_{one} = 1+max(OvLen)$ (find in last page of ovflow chain)

... Selection with Hashing

Select via hashing on unique key *k* (*one*)

```
// select * from R where k = val
f = openFile(relName("R"),READ);
p = hash(val) % nPages(f);
buf = getPage(f, p)
for (i = 0; i < nTuples(buf); i++) {
    tup = getTuple(buf,i);
    if (tup.k == val) return tup;
}
ovp = ovflow(buf);
while (ovp != NO_PAGE) {
    buf = getPage(ovf,ovp);
    for (i = 0; i < nTuples(Buf); i++) {
        tup = getTuple(buf,i);
        if (tup.k == val) return tup;
}   }
```

... Selection with Hashing

Select via hashing on non-unique hash key *k* (*pmr*)

```
// select * from R where k = val
f = openFile(relName("R"),READ);
p = hash(val) % nPages(f);
buf = getPage(f, p)
for (i = 0; i < nTuples(buf); i++) {
    tup = getTuple(buf,i);
    if (tup.k == val) append tup to results
}
ovp = ovflow(buf);
while (ovp != NO_PAGE) {
    buf = getPage(ovf,ovp);
    for (i = 0; i < nTuples(Buf); i++) {
        tup = getTuple(buf,i);
        if (tup.k == val) append tup to results
}   }
```

$Cost_{pmr} = 1 + Ov$

... Selection with Hashing

Hashing does not help with *range* queries** ...

$Cost_{range} = b + b_{ov}$

Selection on attribute *j* which is not hash key ...

$Cost_{one},\ \ Cost_{range},\ \ Cost_{pmr}\ =\ b + b_{ov}$

** unless the hash function is order-preserving (and most aren't)

Insertion with Hashing

Insertion uses similar process to *one* queries.

```
// insert tuple t with key=val into rel R
// f = data file ... ovf = ovflow file
p = hash(val) % nPages(R)
P = getPage(f,p)
if (tup fits in page P)
    { insert t into P; return }
for each overflow page Q of P {
    if (tup fits in page Q)
        { insert t into Q; return }
}
add new overflow page Q
link Q to previous overflow page
insert t into Q
```

$Cost_{insert}$:   Best: $1_r + 1_w$ Worst: $1{+}max(OvLen))_r + 2_w$

Exercise 3: Insertion into Static Hashed File

Consider a file with *b=4*, *c=3*, *d=2*, *h(x) = bits(d,hash(x))*

Insert tuples in alpha order with the following keys and hashes:

k	*hash(k)*		*k*	*hash(k)*		*k*	*hash(k)*		*k*	*hash(k)*
a	10001		g	00000		m	11001		s	01110
b	11010		h	00000		n	01000		t	10011
c	01111		i	10010		o	00110		u	00010
d	01111		j	10110		p	11101		v	11111
e	01100		k	00101		q	00010		w	10000
f	00010		l	00101		r	00000		x	00111

The hash values are the 5 lower-order bits from the full 32-bit hash.

Deletion with Hashing

Similar performance to select:

```
// delete from R where k = val
```

```
// f = data file ... ovf = ovflow file
p = hash(val) % nPages(R)
buf = getPage(f,p)
ndel = delTuples(buf,k,val)
if (ndel > 0) putPage(f,buf,p)
p = ovFlow(buf)
while (p != NO_PAGE) {
    buf = getPage(ovf,p)
    ndel = delTuples(buf,k,val)
    if (ndel > 0) putPage(ovf,buf,p)
    p = ovFlow(buf)
}
```

Extra cost over select is cost of writing back modified blocks.

Method works for both unique and non-unique hash keys.

Problem with Hashing...

So far, discussion of hashing has assumed a fixed file size (fixed *b*).

What size file to use?

- the size we need right now (performance degrades as file overflows)
- the maximum size we might ever need (signifcant waste of space)

Change file size ⇒ change hash function ⇒ rebuild file

Methods for hashing with dynamic files:

- extendible hashing, dynamic hashing (need a directory, no overflows)
- *linear hashing* (expands file "sytematically", no directory, has overflows)

... Problem with Hashing...

All flexible hashing methods ...

- treat hash as 32-bit bit-string
- adjust hashing by using more/less bits

Start with hash function to convert value to bit-string:

```
uint32 hash(unsigned char *val)
```

Require a function to extract *d* bits from bit-string:

```
unit32 bits(int d, uint32 val)
```

Use result of `bits()` as page address.

Exercise 4: Bit Manipulation

1. Write a function to display `uint32` values as `01010110...`

   ```
   char *showBits(uint32 val, char *buf);
   ```

   Analogous to `gets()` (assumes supplied buffer large enough)

2. Write a function to extract the *d* bits of a `uint32`

```
uint32 bits(int d, uint32 val);
```

If $d > 0$, gives low-order bits; if $d < 0$, gives high-order bits

---

... Problem with Hashing...

Important concept for flexible hashing: *splitting*

- consider one page (all tuples have same hash value)
- recompute page numbers by considering one extra bit
- if current page is `101`, new pages have hashes `0101` and `1101`
- some tuples stay in page `0101` (was `101`)
- some tuples move to page `1101` (new page)
- also, rehash any tuples in overflow pages of page `101`

Result: expandable data file, never requiring a complete file rebuild

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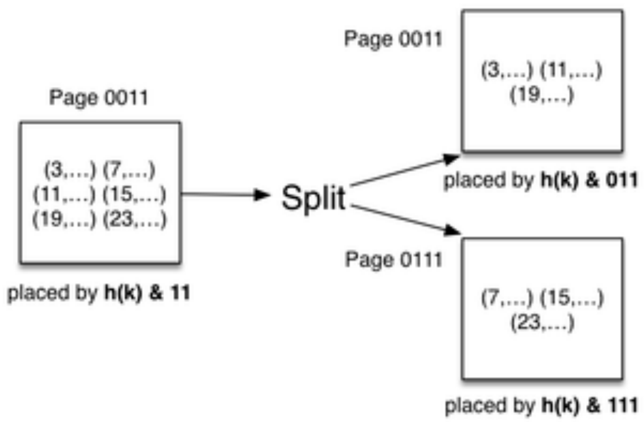
... Problem with Hashing...

Example of splitting:



Tuples only show key value; assume *h(val) = val*

Linear Hashing

File organisation:

- file of primary data blocks
- file of overflow data blocks
- a register called the *split pointer*

Uses systematic method of growing data file ...

- hash function "adapts" to changing address range
- systematic splitting controls length of overflow chains

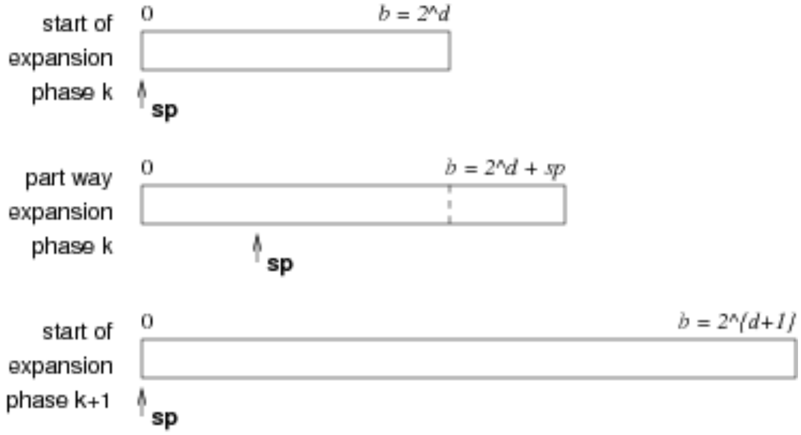
Advantage: does *not* require auxiliary storage for a directory

Disadvantage: requires overflow pages (splits don't occur on full pages)

... Linear Hashing

File grows linearly (one block at a time, at regular intervals).

Has "phases" of expansion; during each phase, *b* doubles.



Selection with Lin.Hashing

If $b=2^d$, the file behaves exactly like standard hashing.

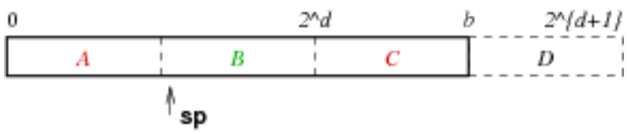
Use *d* bits of hash to compute block address.

```
// select * from R where k = val
h = hash(val);
P = bits(d,h);   // lower-order bits
for each tuple t in page P
         and its overflow pages {
    if (t.k == val) return t;
}
```

Average $Cost_{one}$ = $1+Ov$

... Selection with Lin.Hashing

If b != 2^d, treat different parts of the file differently.



Parts *A* and *C* are treated as if part of a file of size 2^{d+1}.

Part *B* is treated as if part of a file of size 2^d.

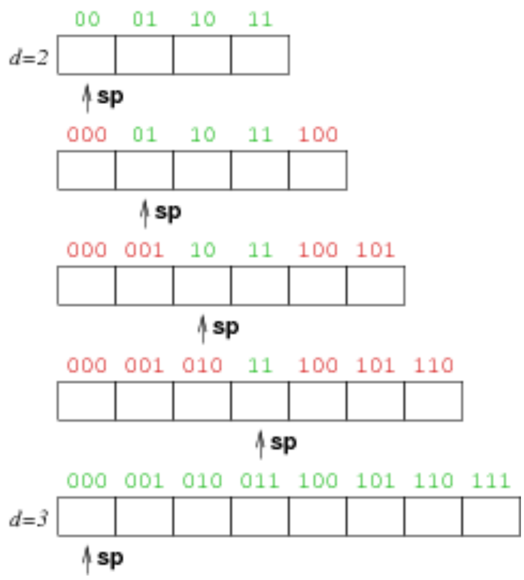
Part *D* does not yet exist (*B* expands into it).

... Selection with Lin.Hashing

Modified search algorithm:

```
// select * from R where k = val
h = hash(val);
P = bits(d,h);
if (P < sp) { P = bits(d+1,h); }
for each tuple t in page P
         and its overflow blocks {
    if (t.k == val) return R;
}
```

File Expansion with Lin.Hashing



Exercise 5: Insertion into Linear Hashed File

Consider a file with *b=4*, *c=3*, *d=2*, *sp=0*, *hash(x)* as above

Insert tuples in alpha order with the following keys and hashes:

k	*hash(k)*		*k*	*hash(k)*		*k*	*hash(k)*		*k*	*hash(k)*
a	10001		g	00000		m	11001		s	01110
b	11010		h	00000		n	01000		t	10011
c	01111		i	10010		o	00110		u	00010
d	01111		j	10110		p	11101		v	11111
e	01100		k	00101		q	00010		w	10000
f	00010		l	00101		r	00000		x	00111

The hash values are the 5 lower-order bits from the full 32-bit hash.

Insertion with Lin.Hashing

Abstract view:

```
P = bits(d,hash(val));
if (P < sp) P = bits(d+1,hash(val));
// bucket P = page P + its overflow pages
for each page Q in bucket P {
    if (space in Q) {
        insert tuple into Q
        break
    }
}
if (no insertion) {
    add new ovflow page to bucket P
    insert tuple into new page
}
if (need to split) {
    partition tuples from bucket sp
```

```
          into buckets sp and sp+2^d
    sp++;
    if (sp == 2^d) { d++; sp = 0; }
}
```

Splitting

How to decide that we "need to split"?

Two approaches to triggering a split:

- split every time a tuple is inserted into full block
- split when load factor reaches threshold (every *k* inserts)

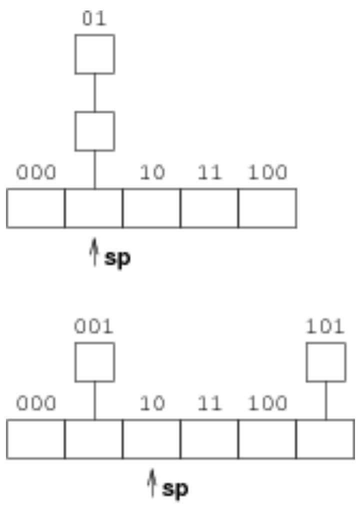
Note: always split block *sp*, even if not full/"current"

Systematic splitting like this ...

- eventually reduces length of every overflow chain
- helps to maintain short average overflow chain length

... Splitting

Splitting process for block *sp*=`01`:



... Splitting

Detailed splitting algorithm:

```
// partitions tuples between two buckets
newp = sp + 2^d; oldp = sp;
buf = getPage(f,sp);
clear(oldBuf); clear(newBuf);
for (i = 0; i < nTuples(buf); i++) {
    tup = getTuple(buf,i);
    p = bits(d+1,hash(tup.k));
    if (p == newp)
        addTuple(newBuf,tup);
    else
        addTuple(oldBuf,tup);
}
p = ovflow(buf);  oldOv = newOv = 0;
while (p != NO_PAGE) {
    ovbuf = getPage(ovf,p);
    for (i = 0; i < nTuples(ovbuf); i++) {
        tup = getTuple(buf,i);
```

```
        p = bits(d+1,hash(tup.k));
        if (p == newp) {
            if (isFull(newBuf)) {
                nextp = nextFree(ovf);
                ovflow(newBuf) = nextp;
                outf = newOv ? f : ovf;
                writePage(outf, newp, newBuf);
                newOv++; newp = nextp; clear(newBuf);
            }
            addTuple(newBuf, tup);
        }
        else {
            if (isFull(oldBuf)) {
                nextp = nextFree(ovf);
                ovflow(oldBuf) = nextp;
                outf = oldOv ? f : ovf;
                writePage(outf, oldp, oldBuf);
                oldOv++; oldp = nextp; clear(oldBuf);
            }
            addTuple(oldBuf, tup);
        }
    }
    addToFreeList(ovf,p);
    p = ovflow(buf);
}
sp++;
if (sp == 2^d) { d++; sp = 0; }
```

Insertion Cost

If no split required, cost same as for standard hashing:

$Cost_{insert}$: Best: $1_r + 1_w$, Avg: $(1+Ov)_r + 1_w$, Worst: $(1+max(Ov))_r + 2_w$

If split occurs, incur $Cost_{insert}$ plus cost of splitting:

- read block *sp* (plus all of its overflow blocks)
- write block *sp* (and its new overflow blocks)
- write block $sp+2^d$ (and its new overflow blocks)

On average, $Cost_{split} = (1+Ov)_r + (2+Ov)_w$

Deletion with Lin.Hashing

Deletion is similar to ordinary static hash file.

But might wish to contract file when enough tuples removed.

Rationale: *r* shrinks, *b* stays large ⇒ wasted space.

Method: remove last bucket in data file (contracts linearly).

Involves a coalesce procedure which is an inverse split.

Hash Files in PostgreSQL

PostgreSQL uses linear hashing on tables which have been:

`create index Ix on R using hash (k);`

Hash file implementation: **`backend/access/hash`**

- **`hashfunc.c`** ... a family of hash functions

- **hashinsert.c** ... insert, with overflows
- **hashpage.c** ... utilities + splitting
- **hashsearch.c** ... iterator for hash files

Based on "A New Hashing Package for Unix", Margo Seltzer, Winter Usenix 1991

... Hash Files in PostgreSQL

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PostgreSQL uses slightly different file organisation ...

- has a single file containing main and overflow pages
- has groups of main pages of size 2^n
- in between groups, arbitrary number of overflow pages
- maintains collection of "split pointers" in header page
- each split pointer indicates start of main page group

If overflow pages become empty, add to free list and re-use.

... Hash Files in PostgreSQL

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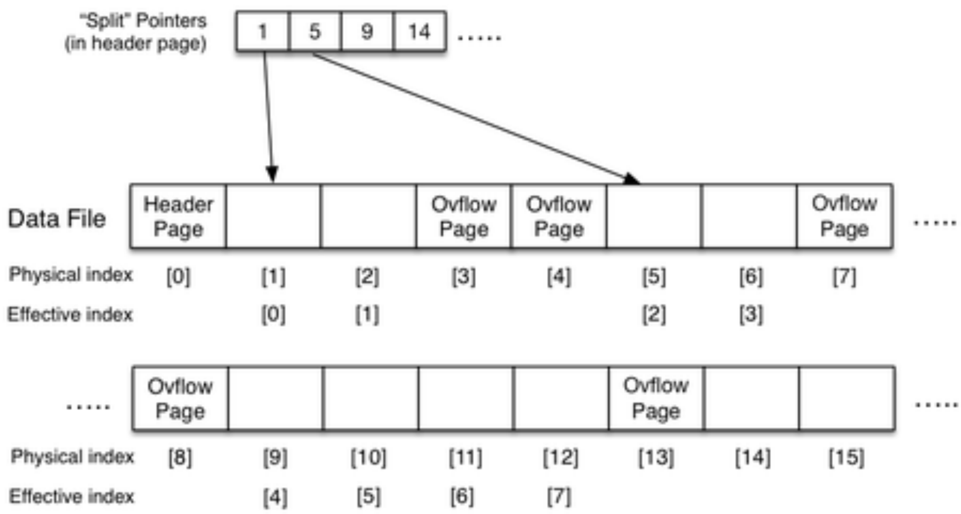
PostgreSQL hash file structure:



... Hash Files in PostgreSQL

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Converting bucket # to page address:

```
// which page is primary page of bucket
uint bucket_to_page(headerp, B) {
   uint *splits = headerp->hashm_spares;
   uint chunk, base, offset, lg2(uint);
   chunk = (B<2) ? 0 : lg2(B+1)-1;
   base = splits[chunk];
   offset = (B<2) ? B : B-(1<chunk);
   return (base + offset);
}
// returns ceil(log_2(n))
int lg2(uint n) {
        int i, v;
        for (i = 0, v = 1; v < n; v <= 1) i++;
        return i;
}
```

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