PostgreSQL Internals Through Pictures

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SRA

Abstract

PostgreSQL is an open-source, full-featured relational database. This presentation gives an overview of how PostgreSQL processes queries.

SQL Query

```
SELECT firstname
FROM friend
WHERE age = 33;
```

Query in Psql

```
test=> SELECT firstname
test-> FROM friend
test-> WHERE age = 33;
    firstname
-----------------
 Sandy
(1 row)
```

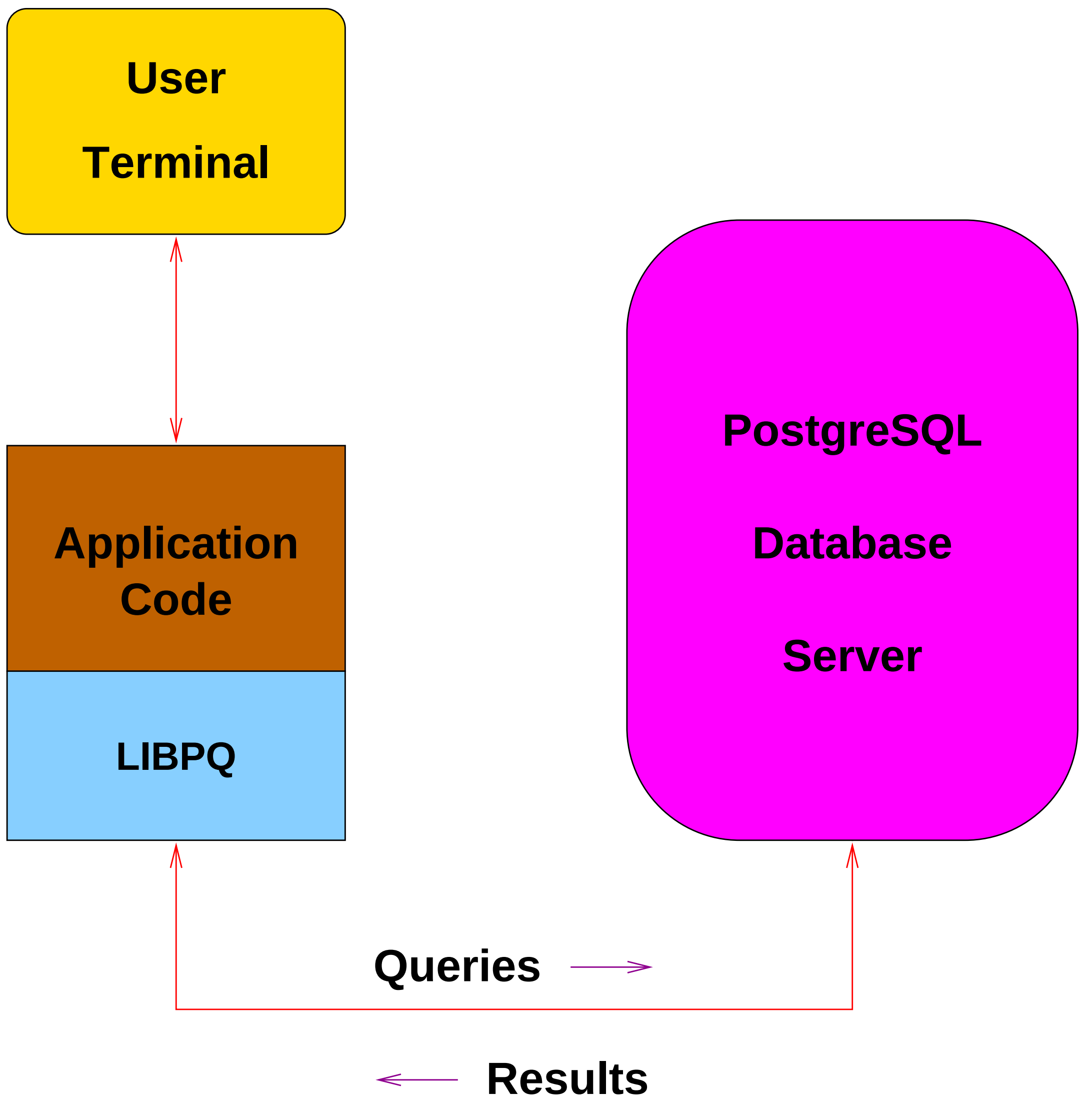
Query Processing

```
test=> SELECT firstname
test-> FROM friend
test-> WHERE age = 33;

[ query is processed ]

    firstname
-----------------
 Sandy
(1 row)
```

Query in Libpq

```
test=> SELECT firstname
test-> FROM friend
test-> WHERE age = 33;

Breakpoint 1, PQexec (conn=0x807a000,
    query=0x8081200 "SELECT firstname\nFROM friend\nWHERE age = 33;")
    at fe-exec.c:1195
```

Libpq


User
Terminal
Application
Code
LIBPQ
PostgreSQL
Database
Server
Queries
Results

TCP/IP Packet

```
17:05:22.715714 family.home.49165 > candle.navpoint.com.5432: P 354:400(46)
ack 61 win 8760 <nop,nop,timestamp 137847 7276138> (DF)

    0000: 00 d0 b7 b9 b6 c8 00 02   b3 04 09 dd 08 00 45 00  ________ ______E_
    0010: 00 62 45 31 40 00 40 06   b1 fe ac 14 00 02 a2 21  _bE1@_@_ _______!
    0020: f5 2e c0 0d 15 38 1c af   94 34 a8 1a 1e 39 80 18  _.___8__ _4___9__
    0030: 22 38 19 d5 00 00 01 01   08 0a 00 02 1a 77 00 6f  "8______ _____w_o
    0040: 06 6a 51 53 45 4c 45 43   54 20 66 69 72 73 74 6e  _jQSELEC T firstn
    0050: 61 6d 65 0a 46 52 4f 4d   20 66 72 69 65 6e 64 0a  ame_FROM  friend_
    0060: 57 48 45 52 45 20 61 67   65 20 3d 20 33 33 3b 00  WHERE ag e = 33;_
```

Query Sent

Result Received

```
FindExec: found "/var/local/postgres/./bin/postgres" using argv[0]
DEBUG:  connection: host=[local] user=postgres database=test
DEBUG:  InitPostgres
DEBUG:  StartTransactionCommand
DEBUG:  query: SELECT firstname
               FROM friend
               WHERE age = 33;

[ query is processed ]

DEBUG:  ProcessQuery
DEBUG:  CommitTransactionCommand
DEBUG:  proc_exit(0)
DEBUG:  shmem_exit(0)
DEBUG:  exit(0)
```

Query Processing

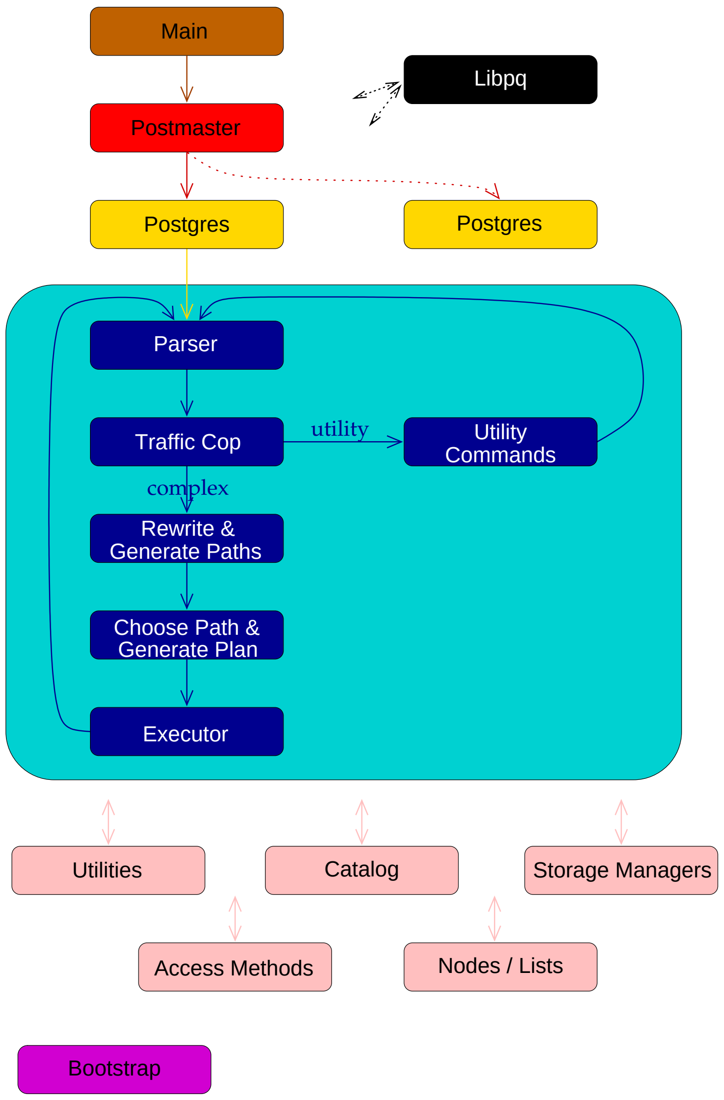
```
FindExec: found "/var/local/postgres/./bin/postmaster" using argv[0]
./bin/postmaster: BackendStartup: pid 3320 user postgres db test socket 5
./bin/postmaster child[3320]: starting with (postgres -d99 -F -d99 -v131072 -p test )
FindExec: found "/var/local/postgres/./bin/postgres" using argv[0]
DEBUG:  connection: host=[local] user=postgres database=test
DEBUG:  InitPostgres
DEBUG:  StartTransactionCommand
DEBUG:  query: SELECT firstname
               FROM friend
               WHERE age = 33;
DEBUG:  parse tree: { QUERY :command 1  :utility <> :resultRelation 0 :into <> :isPortal false :isBinary false :isTemp false :hasAgg
s false :hasSubLinks false :rtable ({ RTE :relname friend :relid 26912  :subquery <> :alias <> :eref { ATTR :relname friend :attrs (
 "firstname"   "lastname"   "city"   "state"   "age" )} :inh true :inFromCl true :checkForRead true :checkForWrite false :checkAsUse
r 0}) :jointree { FROMEXPR :fromlist ({ RANGETBLREF 1 }) :quals { EXPR :typeOid 16  :opType op :oper { OPER :opno 96 :opid 0 :opresu
lttype 16 } :args ({ VAR :varno 1 :varattno 5 :vartype 23 :vartypmod -1  :varlevelsup 0 :varnoold 1 :varoattno 5} { CONST :consttype
 23 :constlen 4 :constbyval true :constisnull false :constvalue  4 [ 33 0 0 0 ] })}} :rowMarks () :targetList ({ TARGETENTRY :resdom
 { RESDOM :resno 1 :restype 1042 :restypmod 19 :resname firstname :reskey 0 :reskeyop 0 :ressortgroupref 0 :resjunk false } :expr {
VAR :varno 1 :varattno 1 :vartype 1042 :vartypmod 19  :varlevelsup 0 :varnoold 1 :varoattno 1}}) :groupClause <> :havingQual <> :dis
tinctClause <> :sortClause <> :limitOffset <> :limitCount <> :setOperations <> :resultRelations ()}
DEBUG:  rewritten parse tree:
DEBUG:  { QUERY :command 1  :utility <> :resultRelation 0 :into <> :isPortal false :isBinary false :isTemp false :hasAggs false :has
SubLinks false :rtable ({ RTE :relname friend :relid 26912  :subquery <> :alias <> :eref { ATTR :relname friend :attrs ( "firstname"
   "lastname"   "city"   "state"   "age" )} :inh true :inFromCl true :checkForRead true :checkForWrite false :checkAsUser 0}) :joint
ree { FROMEXPR :fromlist ({ RANGETBLREF 1 }) :quals { EXPR :typeOid 16  :opType op :oper { OPER :opno 96 :opid 0 :opresulttype 16 }
:args ({ VAR :varno 1 :varattno 5 :vartype 23 :vartypmod -1  :varlevelsup 0 :varnoold 1 :varoattno 5} { CONST :consttype 23 :constle
n 4 :constbyval true :constisnull false :constvalue  4 [ 33 0 0 0 ] })}} :rowMarks () :targetList ({ TARGETENTRY :resdom { RESDOM :r
esno 1 :restype 1042 :restypmod 19 :resname firstname :reskey 0 :reskeyop 0 :ressortgroupref 0 :resjunk false } :expr { VAR :varno 1
 :varattno 1 :vartype 1042 :vartypmod 19  :varlevelsup 0 :varnoold 1 :varoattno 1}}) :groupClause <> :havingQual <> :distinctClause
<> :sortClause <> :limitOffset <> :limitCount <> :setOperations <> :resultRelations ()}
DEBUG:  plan: { SEQSCAN :startup_cost 0.00 :total_cost 22.50 :rows 10 :width 12 :qptargetlist ({ TARGETENTRY :resdom { RESDOM :resno
 1 :restype 1042 :restypmod 19 :resname firstname :reskey 0 :reskeyop 0 :ressortgroupref 0 :resjunk false } :expr { VAR :varno 1 :va
rattno 1 :vartype 1042 :vartypmod 19  :varlevelsup 0 :varnoold 1 :varoattno 1}}) :qpqual ({ EXPR :typeOid 16  :opType op :oper { OPE
R :opno 96 :opid 65 :opresulttype 16 } :args ({ VAR :varno 1 :varattno 5 :vartype 23 :vartypmod -1  :varlevelsup 0 :varnoold 1 :varo
attno 5} { CONST :consttype 23 :constlen 4 :constbyval true :constisnull false :constvalue  4 [ 33 0 0 0 ] })}) :lefttree <> :rightt
ree <> :extprm () :locprm () :initplan <> :nprm 0  :scanrelid 1 }
DEBUG:  ProcessQuery
DEBUG:  CommitTransactionCommand
DEBUG:  proc_exit(0)
DEBUG:  shmem_exit(0)
DEBUG:  exit(0)
./bin/postmaster: reaping dead processes...
./bin/postmaster: CleanupProc: pid 3320 exited with status 0
```

Query Processing

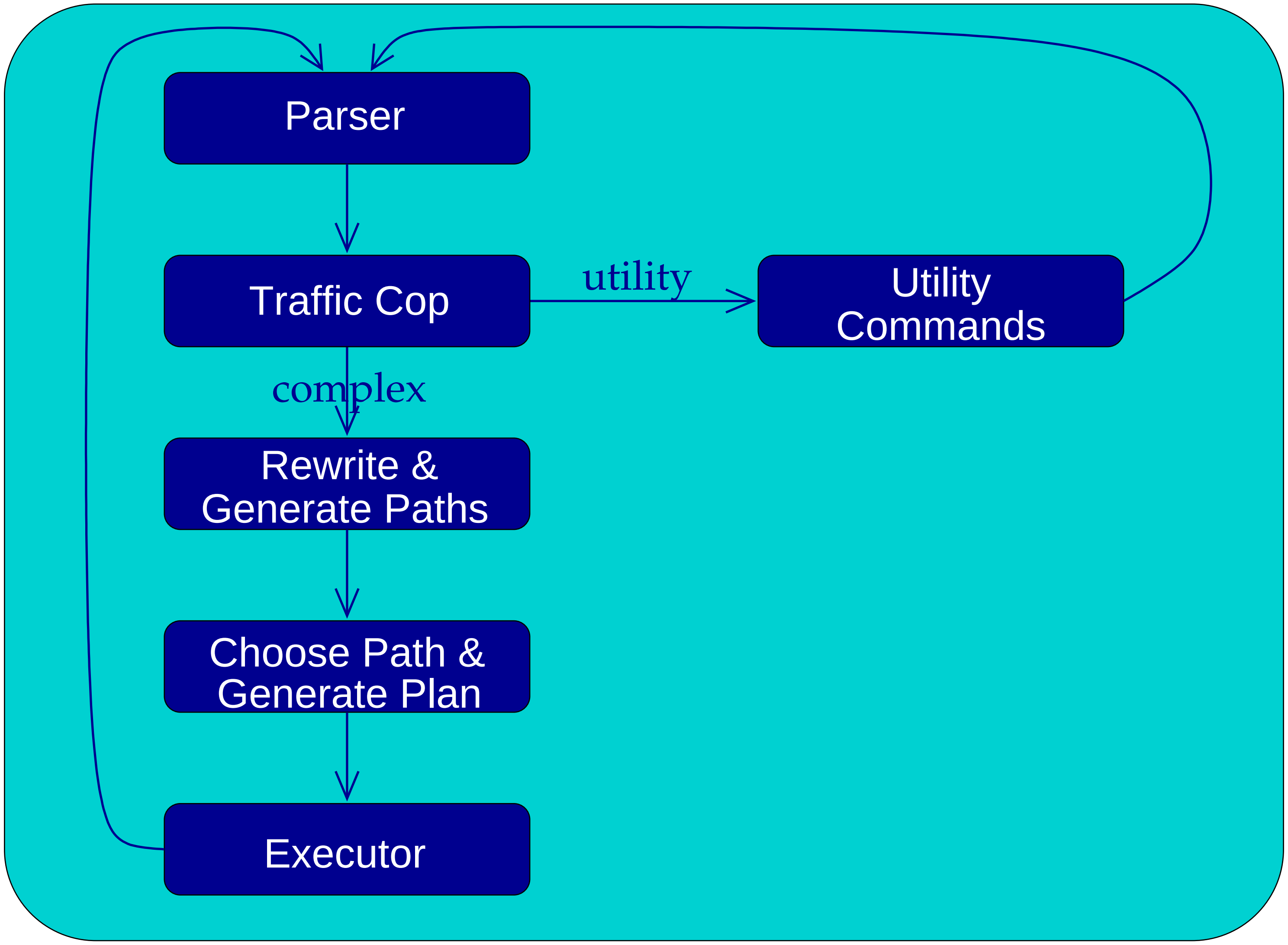
Pretty Output

```
FindExec: found "/var/local/postgres/./bin/postgres" using argv[0]
DEBUG:  connection: host=[local] user=postgres database=test
DEBUG:  InitPostgres
DEBUG:  StartTransactionCommand
DEBUG:  query: SELECT firstname
               FROM friend
               WHERE age = 33;
DEBUG:  parse tree:
{ QUERY
   :command 1
   :utility <>
   :resultRelation 0
   :into <>
   :isPortal false
   :isBinary false
   :isTemp false
   :hasAggs false
   :hasSubLinks false
   :rtable (
      { RTE
      :relname friend
      :relid 26912
      :subquery <>
      :alias <>
      :eref
         { ATTR
         :relname friend
         :attrs ( "firstname"   "lastname"   "city"   "state"   "age" )
         }

      :inh true
      :inFromCl true
      :checkForRead true
      :checkForWrite false
      :checkAsUser 0
      }
   )
```

Backend Flowchart



Backend Flowchart - Magnified



Scanner Identifier Rule

```
identifier      {letter}{letter_or_digit}*

{identifier}    {
                    int i;
                    ScanKeyword     *keyword;

                    for(i = 0; yytext[i]; i++)
                        if (isupper((unsigned char) yytext[i]))
                            yytext[i] = tolower((unsigned char) yytext[i]);
                    if (i >= NAMEDATALEN)
                    {
                        elog(NOTICE, "identifier \"%s\" will be truncated to \"%.*s\"",
                             yytext, NAMEDATALEN-1, yytext);
                        yytext[NAMEDATALEN-1] = '\0';
                    }
                    keyword = ScanKeywordLookup((char*)yytext);
                    if (keyword != NULL) {
                        return keyword->value;
                    }
                    else
                    {
                        yylval.str = pstrdup((char*)yytext);
                        return IDENT;
                    }
                }
```

Scanner Numeric Rules

```
digit           [0-9]
letter          [\200-\377_A-Za-z]
letter_or_digit [\200-\377_A-Za-z0-9]

integer         {digit}+
decimal         (({digit}*\.{digit}+)|({digit}+\.{digit}*))
real            ((({digit}*\.{digit}+)|({digit}+\.{digit}*)|({digit}+))([Ee][-+]?{digit}+))

{integer}       {
                    char* endptr;

                    errno = 0;
                    yylval.ival = strtol((char *)yytext, &endptr, 10);
                    if (*endptr != '\0' || errno == ERANGE)
                    {
                        yylval.str = pstrdup((char*)yytext);
                        return FCONST;
                    }
                    return ICONST;
                }
{decimal}       {
                    yylval.str = pstrdup((char*)yytext);
                    return FCONST;
                }
{real}          {
                    yylval.str = pstrdup((char*)yytext);
                    return FCONST;
                }
```

Scanner Output

```
--accepting rule at line 476 ("SELECT")
--accepting rule at line 254 (" ")
--accepting rule at line 476 ("firstname")
--accepting rule at line 254 ("\n")
--accepting rule at line 476 ("FROM")
--accepting rule at line 254 (" ")
--accepting rule at line 476 ("friend")
--accepting rule at line 254 ("\n")
--accepting rule at line 476 ("WHERE")
--accepting rule at line 254 (" ")
--accepting rule at line 476 ("age")
--accepting rule at line 254 (" ")
--accepting rule at line 377 ("=")
--accepting rule at line 254 (" ")
--accepting rule at line 453 ("33")
--accepting rule at line 377 (";")
--(end of buffer or a NUL)
--EOF (start condition 0)
```

SELECT Parser Action

```
simple_select: SELECT opt_distinct target_list
             into_clause from_clause where_clause
             group_clause having_clause
                {
                    SelectStmt *n = makeNode(SelectStmt);
                    n->distinctClause = $2;
                    n->targetList = $3;
                    n->istemp = (bool) ((Value *) lfirst($4))->val.ival;
                    n->into = (char *) lnext($4);
                    n->fromClause = $5;
                    n->whereClause = $6;
                    n->groupClause = $7;
                    n->havingClause = $8;
                    $$ = (Node *)n;
                }
```

SelectStmt Structure

```
typedef struct SelectStmt
{
    NodeTag     type;
    /*
     * These fields are used only in "leaf" SelectStmts.
     */
    List       *distinctClause; /* NULL, list of DISTINCT ON exprs, or
                                 * lcons(NIL,NIL) for all (SELECT
                                 * DISTINCT) */
    char       *into;           /* name of table (for select into table) */
    bool        istemp;         /* into is a temp table? */
    List       *targetList;     /* the target list (of ResTarget) */
    List       *fromClause;     /* the FROM clause */
    Node       *whereClause;    /* WHERE qualification */
    List       *groupClause;    /* GROUP BY clauses */
    Node       *havingClause;   /* HAVING conditional-expression */
    /*
     * These fields are used in both "leaf" SelectStmts and upper-level
     * SelectStmts.  portalname/binary may only be set at the top level.
     */
    List       *sortClause;     /* sort clause (a list of SortGroupBy's) */
    char       *portalname;     /* the portal (cursor) to create */
    bool        binary;         /* a binary (internal) portal? */
    Node       *limitOffset;    /* # of result tuples to skip */
    Node       *limitCount;     /* # of result tuples to return */
    List       *forUpdate;      /* FOR UPDATE clause */
    /*
     * These fields are used only in upper-level SelectStmts.
     */
    SetOperation op;            /* type of set op */
    bool        all;            /* ALL specified? */
    struct SelectStmt *larg;    /* left child */
    struct SelectStmt *rarg;    /* right child */
    /* Eventually add fields for CORRESPONDING spec here */
} SelectStmt;
```

Parsing

```
Starting parse
Entering state 0
Reading a token: Next token is 377 (SELECT)
Shifting token 377 (SELECT), Entering state 15
Reading a token: Next token is 514 (IDENT)
Reducing via rule 534 (line 3430),  -> opt_distinct
state stack now 0 15
Entering state 324
Next token is 514 (IDENT)
Shifting token 514 (IDENT), Entering state 496
Reading a token: Next token is 314 (FROM)
Reducing via rule 871 (line 5391), IDENT  -> ColId
state stack now 0 15 324
Entering state 531
Next token is 314 (FROM)
Reducing via rule 789 (line 4951),  -> opt_indirection
state stack now 0 15 324 531
Entering state 755
Next token is 314 (FROM)
Reducing via rule 760 (line 4591), ColId opt_indirection  -> c_expr
state stack now 0 15 324
Entering state 520
Reducing via rule 693 (line 4272), c_expr  -> a_expr
state stack now 0 15 324
Entering state 519
Next token is 314 (FROM)
Reducing via rule 833 (line 5183), a_expr  -> target_el
state stack now 0 15 324
Entering state 524
Reducing via rule 831 (line 5171), target_el  -> target_list
state stack now 0 15 324
Entering state 523
Next token is 314 (FROM)
Reducing via rule 518 (line 3382),  -> into_clause
```

Scanning and Parsing

```
Starting parse
Entering state 0
Reading a token:
--(end of buffer or a NUL)
--accepting rule at line 476 ("SELECT")
Next token is 377 (SELECT)
Shifting token 377 (SELECT), Entering state 15
Reading a token:
--accepting rule at line 254 (" ")
--accepting rule at line 476 ("firstname")
Next token is 514 (IDENT)
Reducing via rule 534 (line 3430),  -> opt_distinct
state stack now 0 15
Entering state 324
Next token is 514 (IDENT)
Shifting token 514 (IDENT), Entering state 496
Reading a token:
--accepting rule at line 254 ("\n")
--accepting rule at line 476 ("FROM")
Next token is 314 (FROM)
Reducing via rule 871 (line 5391), IDENT  -> ColId
state stack now 0 15 324
Entering state 531
Next token is 314 (FROM)
Reducing via rule 789 (line 4951),  -> opt_indirection
state stack now 0 15 324 531
Entering state 755
Next token is 314 (FROM)
```

List Structures

```
typedef struct List
{
    NodeTag     type;
    union
    {
        void        *ptr_value;
        int          int_value;
    }           elem;
    struct List *next;
} List;

#define    NIL          ((List *) NULL)

#define lfirst(l)       ((l)->elem.ptr_value)
#define lnext(l)        ((l)->next)
#define lsecond(l)      lfirst(lnext(l))

#define lfirsti(l)      ((l)->elem.int_value)

#define foreach(_elt_,_list_)   \
    for(_elt_=(_list_); _elt_!=NIL; _elt_=lnext(_elt_))
```

List Support Functions

Function	Description
lfirst	returns value stored in List
lnext	returns pointer to next in List
foreach	loops through List
length	returns length of List
nth	returns nth element from List
makeList1	creates a new list
lcons	adds value to front of List
lappend	appends value to end of List
nconc	concatenates two Lists

There are versions of these functions for storing integers rather than pointers.

Range Table Entry Structure

```
typedef struct RangeTblEntry
{
    NodeTag     type;
    /*
     * Fields valid for a plain relation RTE (else NULL/zero):
     */
    char       *relname;       /* real name of the relation */
    Oid         relid;         /* OID of the relation */
    /*
     * Fields valid for a subquery RTE (else NULL):
     */
    Query      *subquery;      /* the sub-query */
    /*
     * Fields valid in all RTEs:
     */
    Attr       *alias;         /* user-written alias clause, if any */
    Attr       *eref;          /* expanded reference names */
    bool        inh;           /* inheritance requested? */
    bool        inFromCl;      /* present in FROM clause */
    bool        checkForRead;  /* check rel for read access */
    bool        checkForWrite; /* check rel for write access */
    Oid         checkAsUser;   /* if not zero, check access as this user */
} RangeTblEntry;
```

Var Structure

```
typedef struct Var
{
    NodeTag     type;
    Index       varno;      /* index of this var’s relation in the range
                             * table (could also be INNER or OUTER) */
    AttrNumber  varattno;   /* attribute number of this var, or zero for all */
    Oid         vartype;    /* pg_type tuple OID for the type of this var */
    int32       vartypmod;  /* pg_attribute typmod value */
    Index       varlevelsup;
                            /* for subquery variables referencing outer
                             * relations; 0 in a normal var, >0 means N
                             * levels up */
    Index       varnoold;   /* original value of varno, for debugging */
    AttrNumber  varoattno;  /* original value of varattno */
} Var;
```

TargetEntry Structure

```
typedef struct TargetEntry
{
    NodeTag     type;
    Resdom     *resdom;         /* fjoin overload this to be a list?? */
    Fjoin      *fjoin;
    Node       *expr;
} TargetEntry;
```

Query Structure

```
typedef struct Query
{
    NodeTag     type;

    CmdType     commandType;    /* select|insert|update|delete|utility */

    Node       *utilityStmt;    /* non-null if this is a non-optimizable
                                 * statement */

    int         resultRelation; /* target relation (index into rtable) */
    char       *into;           /* portal (cursor) name */
    bool        isPortal;       /* is this a retrieve into portal? */
    bool        isBinary;       /* binary portal? */
    bool        isTemp;         /* is 'into' a temp table? */

    bool        hasAggs;        /* has aggregates in tlist or havingQual */
    bool        hasSubLinks;    /* has subquery SubLink */

    List       *rtable;         /* list of range table entries */
    FromExpr   *jointree;       /* table join tree (FROM and WHERE clauses) */

    List       *rowMarks;       /* integer list of RT indexes of relations
                                 * that are selected FOR UPDATE */

    List       *targetList;     /* target list (of TargetEntry) */

    List       *groupClause;    /* a list of GroupClause's */

    Node       *havingQual;     /* qualifications applied to groups */

    List       *distinctClause; /* a list of SortClause's */

    List       *sortClause;     /* a list of SortClause's */

    Node       *limitOffset;    /* # of result tuples to skip */
    Node       *limitCount;     /* # of result tuples to return */

    Node       *setOperations;  /* set-operation tree if this is top level
                                 * of a UNION/INTERSECT/EXCEPT query */
    List       *resultRelations; /* integer list of RT indexes, or NIL */

    /* internal to planner */
    List       *base_rel_list;  /* list of base-relation RelOptInfos */
    List       *join_rel_list;  /* list of join-relation RelOptInfos */
    List       *equi_key_list;  /* list of lists of equijoined
                                 * PathKeyItems */
    List       *query_pathkeys; /* pathkeys for query_planner()'s result */
} Query;
```

Query Output

```
{ QUERY
   :command 3
   :utility <>
   :resultRelation 1
   :into <>
   :isPortal false
   :isBinary false
   :isTemp false
   :hasAggs false
   :hasSubLinks false
   :rtable (
      { RTE
      :relname friend
      :relid 26914
      :subquery <>
      :alias <>
      :eref
         { ATTR
         :relname friend
         :attrs ( "firstname"   "lastname"   "city"   "state"   "age" )
         }

      :inh false
      :inFromCl false
      :checkForRead false
      :checkForWrite true
      :checkAsUser 0
      }
   )

   :jointree
      { FROMEXPR
      :fromlist <>
      :quals <>
      }

   :rowMarks ()

   :targetList (
      { TARGETENTRY
      :resdom
         { RESDOM
         :resno 1
         :restype 1042
         :restypmod 19
         :resname firstname
         :reskey 0
         :reskeyop 0
         :ressortgroupref 0
```

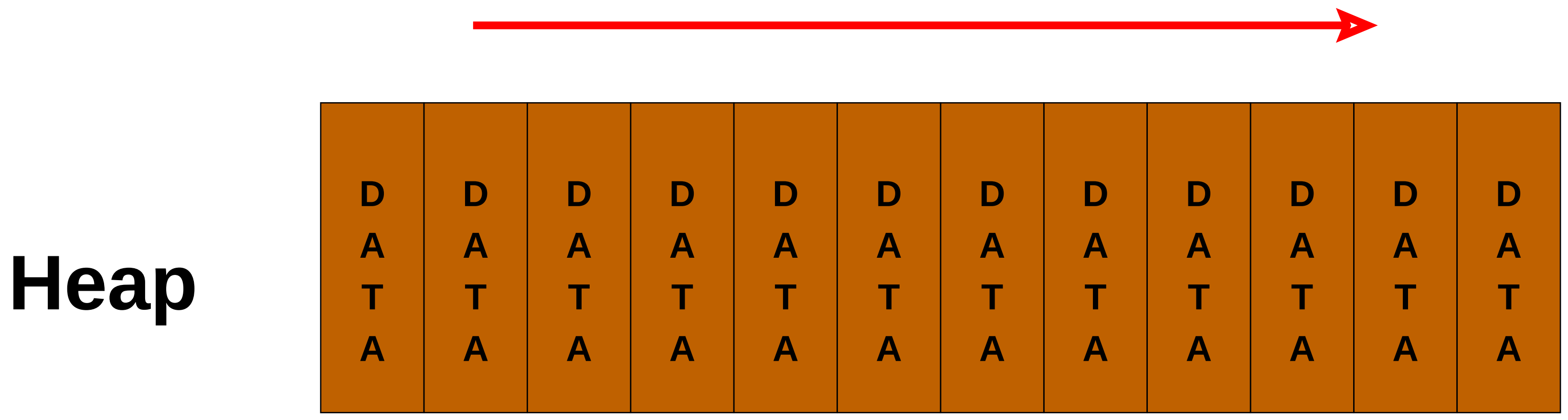
Optimizer

- Scan Methods
- Join Methods
- Join Order

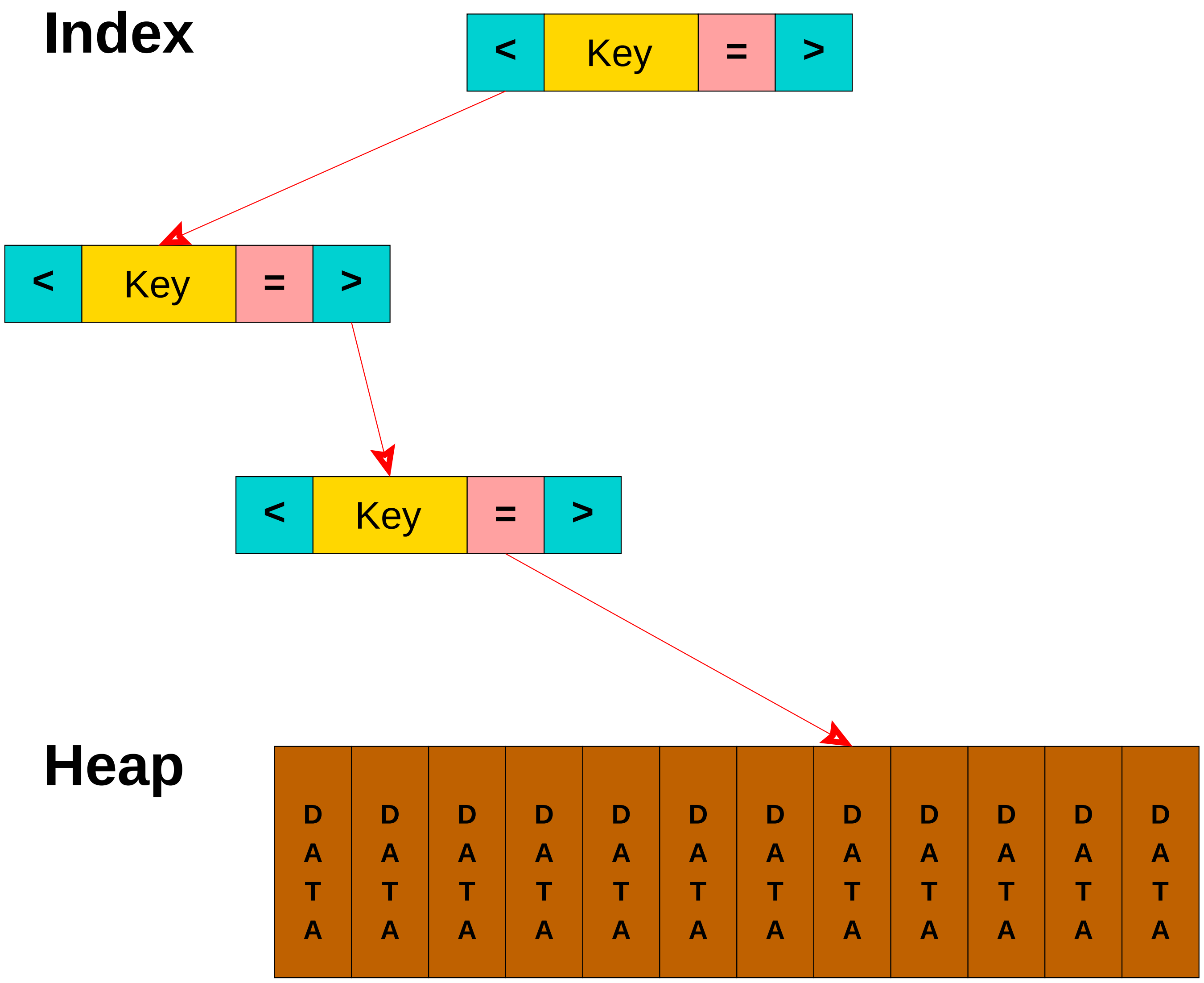
Scan Methods

- Sequential Scan
- Index Scan

Sequential Scan



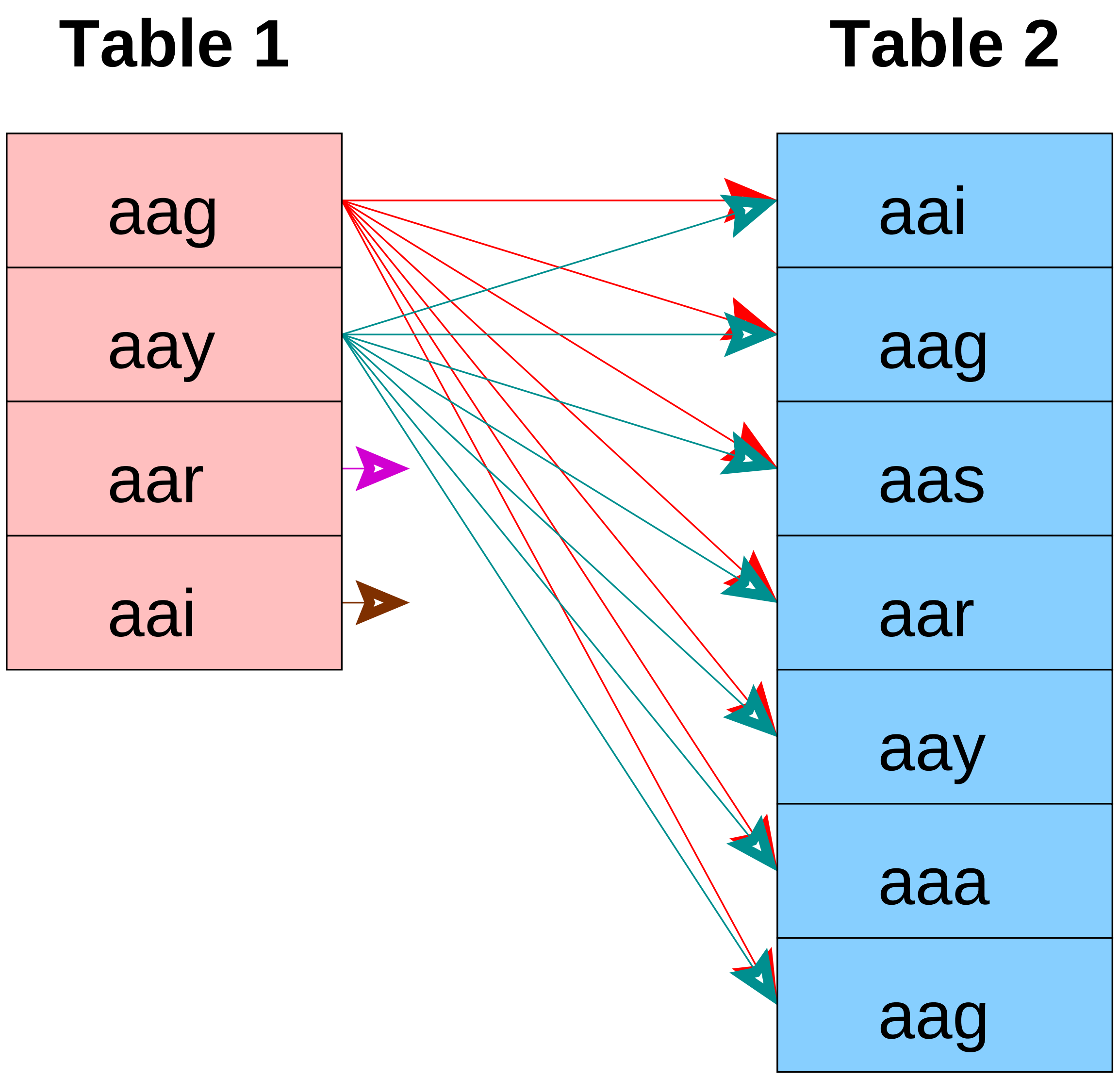
Btree Index Scan



Join Methods

- Nested Loop
- Merge Join
- Hash Join

Nested Loop Join



Merge Join

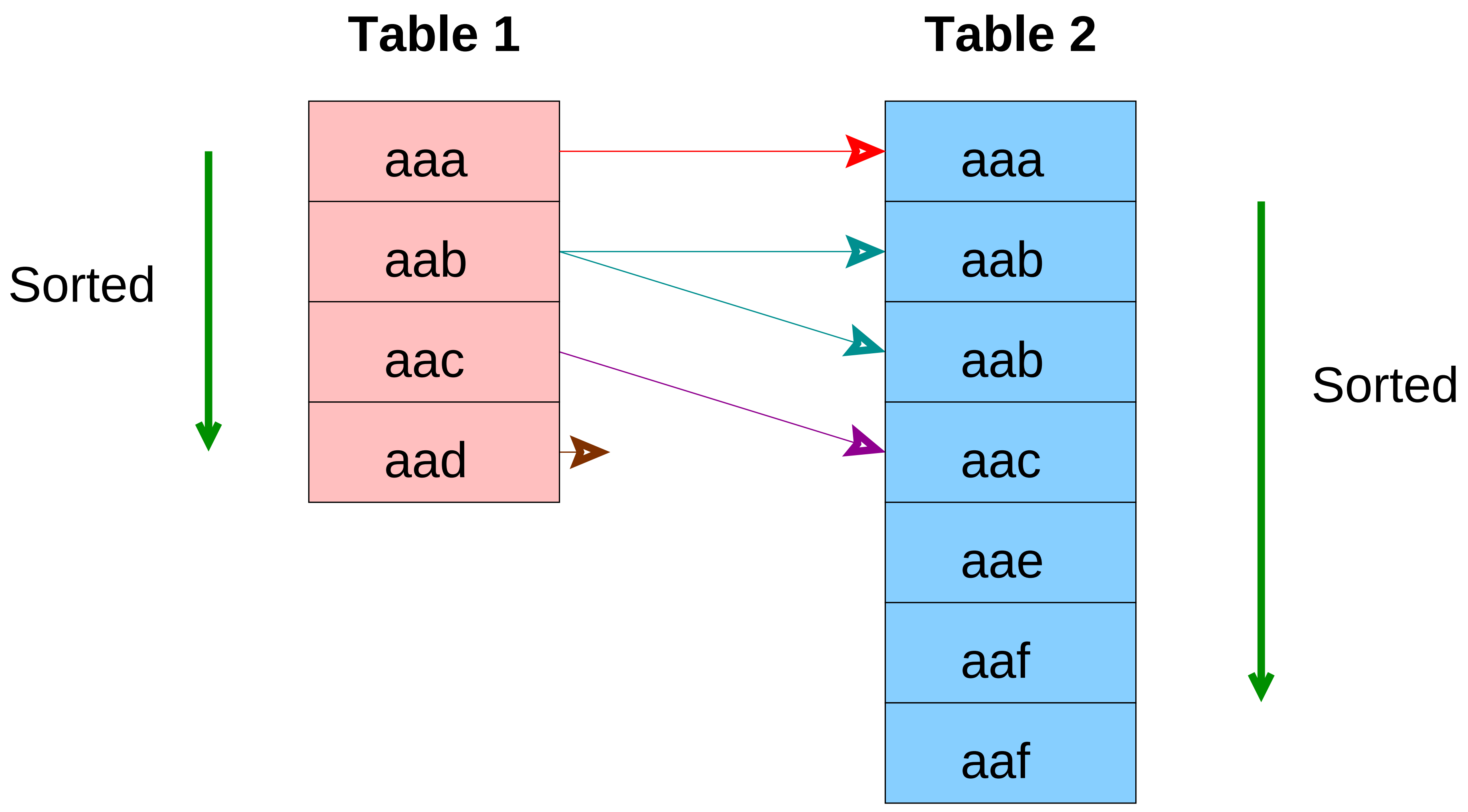


Table 1
Table 2
Sorted
aaa
aab
aac
aad
aaa
aab
aab
aac
aae
aaf
aaf
Sorted

Hash Join

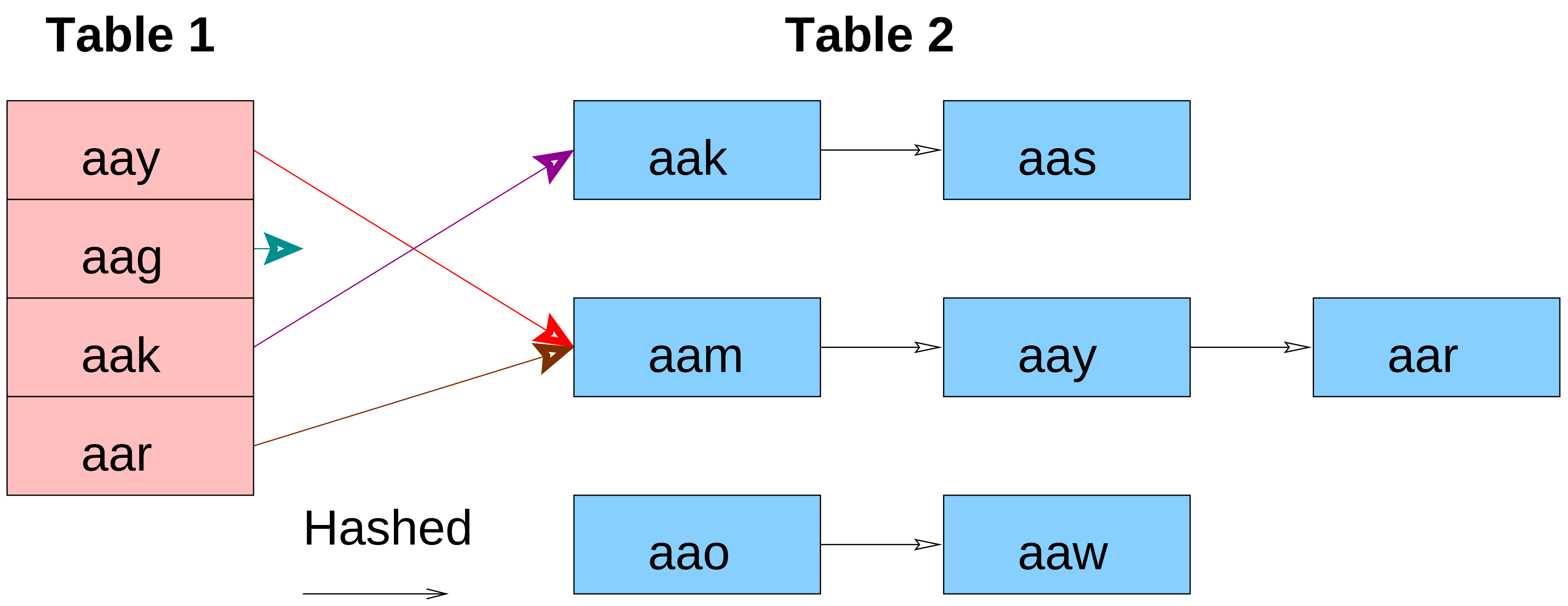


Table 1
Table 2
aay
aag
aak
aar
aak
aas
aam
aay
aar
aao
aaw
Hashed

Path Structure

```
typedef struct Path
{
    NodeTag     type;

    RelOptInfo *parent;         /* the relation this path can build */

    /* estimated execution costs for path (see costsize.c for more info) */
    Cost        startup_cost;   /* cost expended before fetching any
                                 * tuples */
    Cost        total_cost;     /* total cost (assuming all tuples
                                 * fetched) */

    NodeTag     pathtype;       /* tag identifying scan/join method */
    /* XXX why is pathtype separate from the NodeTag? */

    List       *pathkeys;       /* sort ordering of path’s output */
    /* pathkeys is a List of Lists of PathKeyItem nodes; see above */
} Path;
```

PathKeys Structure

```
typedef struct PathKeyItem
{
    NodeTag     type;

    Node       *key;            /* the item that is ordered */
    Oid         sortop;         /* the ordering operator ('<' op) */

    /*
     * key typically points to a Var node, ie a relation attribute, but it
     * can also point to a Func clause representing the value indexed by a
     * functional index.  Someday we might allow arbitrary expressions as
     * path keys, so don't assume more than you must.
     */
} PathKeyItem;
```

RelOptInfo Structure

```
typedef struct RelOptInfo
{
    NodeTag     type;

    /* all relations included in this RelOptInfo */
    Relids      relids;         /* integer list of base relids (RT
                                 * indexes) */

    /* size estimates generated by planner */
    double      rows;           /* estimated number of result tuples */
    int         width;          /* estimated avg width of result tuples */

    /* materialization information */
    List       *targetlist;
    List       *pathlist;       /* Path structures */
    struct Path *cheapest_startup_path;
    struct Path *cheapest_total_path;
    bool        pruneable;

    /* information about a base rel (not set for join rels!) */
    bool        issubquery;
    bool        indexed;
    long        pages;
    double      tuples;
    struct Plan *subplan;

    /* used by various scans and joins: */
    List       *baserestrictinfo;       /* RestrictInfo structures (if
                                         * base rel) */
    Cost        baserestrictcost;       /* cost of evaluating the above */
    Relids      outerjoinset;           /* integer list of base relids */
    List       *joininfo;       /* JoinInfo structures */
    List       *innerjoin;      /* potential indexscans for nestloop joins */

    /*
     * innerjoin indexscans are not in the main pathlist because they are
     * not usable except in specific join contexts; we have to test before
     * seeing whether they can be used.
     */
} RelOptInfo;
```

Three-Table Join Query

```
SELECT  part.price
FROM    customer, salesorder, part
WHERE   customer.customer_id = salesorder.customer_id AND
        salesorder.part = part.part_id
```

Three-Table Join, Pass 1, Part 1

```
(2 3 ): rows=575 width=76
        path list:
        HashJoin rows=575 cost=3.57..41.90
          clauses=(salesorder.part_id = part.part_id)
                SeqScan(2) rows=575 cost=0.00..13.75
                SeqScan(3) rows=126 cost=0.00..3.26
        Nestloop rows=575 cost=0.00..1178.70
                SeqScan(2) rows=575 cost=0.00..13.75
                IdxScan(3) rows=126 cost=0.00..2.01
        Nestloop rows=575 cost=0.00..1210.28
          pathkeys=((salesorder.customer_id, customer.customer_id) )
                IdxScan(2) rows=575 cost=0.00..45.33
                  pathkeys=((salesorder.customer_id, customer.customer_id) )
                IdxScan(3) rows=126 cost=0.00..2.01

        cheapest startup path:
        Nestloop rows=575 cost=0.00..1178.70
                SeqScan(2) rows=575 cost=0.00..13.75
                IdxScan(3) rows=126 cost=0.00..2.01

        cheapest total path:
        HashJoin rows=575 cost=3.57..41.90
          clauses=(salesorder.part_id = part.part_id)
                SeqScan(2) rows=575 cost=0.00..13.75
                SeqScan(3) rows=126 cost=0.00..3.26
```

Three-Table Join, Pass 1, Part 2

```
(1 2 ): rows=575 width=76
        path list:
        HashJoin rows=575 cost=3.00..40.75
          clauses=(salesorder.customer_id = customer.customer_id)
                SeqScan(2) rows=575 cost=0.00..13.75
                SeqScan(1) rows=80 cost=0.00..2.80
        MergeJoin rows=575 cost=0.00..64.39
          clauses=(salesorder.customer_id = customer.customer_id)
                IdxScan(1) rows=80 cost=0.00..10.88
                  pathkeys=((salesorder.customer_id, customer.customer_id) )
                IdxScan(2) rows=575 cost=0.00..45.33
                  pathkeys=((salesorder.customer_id, customer.customer_id) )

        cheapest startup path:
        MergeJoin rows=575 cost=0.00..64.39
          clauses=(salesorder.customer_id = customer.customer_id)
                IdxScan(1) rows=80 cost=0.00..10.88
                  pathkeys=((salesorder.customer_id, customer.customer_id) )
                IdxScan(2) rows=575 cost=0.00..45.33
                  pathkeys=((salesorder.customer_id, customer.customer_id) )

        cheapest total path:
        HashJoin rows=575 cost=3.00..40.75
          clauses=(salesorder.customer_id = customer.customer_id)
                SeqScan(2) rows=575 cost=0.00..13.75
                SeqScan(1) rows=80 cost=0.00..2.80
```

Three-Table Join, Pass 2, Part 1

```
(2 3 1 ): rows=575 width=112
        path list:
        HashJoin rows=575 cost=6.58..68.90
          clauses=(salesorder.customer_id = customer.customer_id)
                HashJoin rows=575 cost=3.57..41.90
                  clauses=(salesorder.part_id = part.part_id)
                        SeqScan(2) rows=575 cost=0.00..13.75
                        SeqScan(3) rows=126 cost=0.00..3.26
                SeqScan(1) rows=80 cost=0.00..2.80
        HashJoin rows=575 cost=3.57..92.54
          clauses=(salesorder.part_id = part.part_id)
                MergeJoin rows=575 cost=0.00..64.39
                  clauses=(salesorder.customer_id = customer.customer_id)
                        IdxScan(1) rows=80 cost=0.00..10.88
                          pathkeys=((salesorder.customer_id, customer.customer_id) )
                        IdxScan(2) rows=575 cost=0.00..45.33
                          pathkeys=((salesorder.customer_id, customer.customer_id) )
                SeqScan(3) rows=126 cost=0.00..3.26
        HashJoin rows=575 cost=3.00..1205.70
          clauses=(salesorder.customer_id = customer.customer_id)
                Nestloop rows=575 cost=0.00..1178.70
                        SeqScan(2) rows=575 cost=0.00..13.75
                        IdxScan(3) rows=126 cost=0.00..2.01
                SeqScan(1) rows=80 cost=0.00..2.80
```

Three-Table Join, Pass 2, Part 2

```
MergeJoin rows=575 cost=0.00..1229.35
  clauses=(salesorder.customer_id = customer.customer_id)
        Nestloop rows=575 cost=0.00..1210.28
          pathkeys=((salesorder.customer_id, customer.customer_id) )
                IdxScan(2) rows=575 cost=0.00..45.33
                  pathkeys=((salesorder.customer_id, customer.customer_id) )
                IdxScan(3) rows=126 cost=0.00..2.01
        IdxScan(1) rows=80 cost=0.00..10.88
          pathkeys=((salesorder.customer_id, customer.customer_id) )

cheapest startup path:
MergeJoin rows=575 cost=0.00..1229.35
  clauses=(salesorder.customer_id = customer.customer_id)
        Nestloop rows=575 cost=0.00..1210.28
          pathkeys=((salesorder.customer_id, customer.customer_id) )
                IdxScan(2) rows=575 cost=0.00..45.33
                  pathkeys=((salesorder.customer_id, customer.customer_id) )
                IdxScan(3) rows=126 cost=0.00..2.01
        IdxScan(1) rows=80 cost=0.00..10.88
          pathkeys=((salesorder.customer_id, customer.customer_id) )

cheapest total path:
HashJoin rows=575 cost=6.58..68.90
  clauses=(salesorder.customer_id = customer.customer_id)
        HashJoin rows=575 cost=3.57..41.90
          clauses=(salesorder.part_id = part.part_id)
                SeqScan(2) rows=575 cost=0.00..13.75
                SeqScan(3) rows=126 cost=0.00..3.26
        SeqScan(1) rows=80 cost=0.00..2.80
```

Plan Structure

```
typedef struct Plan
{
    NodeTag     type;

    /* estimated execution costs for plan (see costsize.c for more info) */
    Cost        startup_cost;   /* cost expended before fetching any
                                 * tuples */
    Cost        total_cost;     /* total cost (assuming all tuples
                                 * fetched) */

    /*
     * planner’s estimate of result size (note: LIMIT, if any, is not
     * considered in setting plan_rows)
     */
    double      plan_rows;      /* number of rows plan is expected to emit */
    int         plan_width;     /* average row width in bytes */

    EState     *state;          /* at execution time, state’s of
                                 * individual nodes point to one EState
                                 * for the whole top-level plan */
    List       *targetlist;
    List       *qual;           /* implicitly-ANDed qual conditions */
    struct Plan *lefttree;
    struct Plan *righttree;
    List       *extParam;       /* indices of _all_ _external_ PARAM_EXEC
                                 * for this plan in global
                                 * es_param_exec_vals. Params from
                                 * setParam from initPlan-s are not
                                 * included, but their execParam-s are
                                 * here!!! */
    List       *locParam;       /* someones from setParam-s */
    List       *chgParam;       /* list of changed ones from the above */
    List       *initPlan;       /* Init Plan nodes (un-correlated expr
                                 * subselects) */
    List       *subPlan;        /* Other SubPlan nodes */

    /*
     * We really need in some TopPlan node to store range table and
     * resultRelation from Query there and get rid of Query itself from
     * Executor. Some other stuff like below could be put there, too.
     */
    int         nParamExec;     /* Number of them in entire query. This is
                                 * to get Executor know about how many
                                 * param_exec there are in query plan. */
} Plan;
```

Plan Output

```
DEBUG:  plan:

{ SEQSCAN
   :startup_cost 0.00
   :total_cost 22.50
   :rows 10
   :width 12
   :qptargetlist (
      { TARGETENTRY
      :resdom
         { RESDOM
         :resno 1
         :restype 1042
         :restypmod 19
         :resname firstname
         :reskey 0
         :reskeyop 0
         :ressortgroupref 0
         :resjunk false
         }

      :expr
         { VAR
         :varno 1
         :varattno 1
         :vartype 1042
         :vartypmod 19
         :varlevelsup 0
         :varnoold 1
         :varoattno 1
         }
      }
   )
```

Plan Output - Three-Table Join

```
DEBUG:  plan:

{ HASHJOIN
   :startup_cost 6.58
   :total_cost 68.90
   :rows 575
   :width 112
   :qptargetlist (
      { TARGETENTRY
      :resdom
         { RESDOM
         :resno 1
         :restype 19
         :restypmod -1
         :resname relname
         :reskey 0
         :reskeyop 0
         :ressortgroupref 0
         :resjunk false
         }

      :expr
         { VAR
         :varno 65000
         :varattno 1
         :vartype 19
         :vartypmod -1
         :varlevelsup 0
         :varnoold 1
         :varoattno 1
         }
      }
```

Result Returned

```
test=> SELECT firstname
test-> FROM friend
test-> WHERE age = 33;

    1: firstname           (typeid = 1042, len = -1, typmod = 19, byval = f)
    ----
    1: firstname = "Sandy" (typeid = 1042, len = -1, typmod = 19, byval = f)
    ----

    firstname
-----------------
 Sandy
(1 row)
```

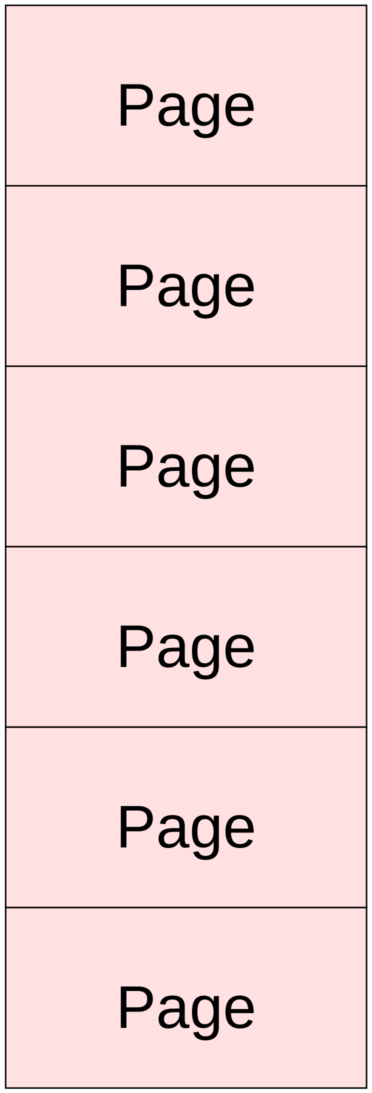
Statistics - Part 1

```
PARSER STATISTICS
  system usage stats:
        0.000002 elapsed 0.000000 user 0.000001 system sec
        [0.009992 user 0.049961 sys total]
        0/0 [0/1] filesystem blocks in/out
        0/0 [0/0] page faults/reclaims, 0 [0] swaps
        0 [0] signals rcvd, 0/0 [2/2] messages rcvd/sent
        0/0 [2/6] voluntary/involuntary context switches
  postgres usage stats:
        Shared blocks:          0 read,          0 written, buffer hit rate = 0.00%
        Local  blocks:          0 read,          0 written, buffer hit rate = 0.00%
        Direct blocks:          0 read,          0 written
PARSE ANALYSIS STATISTICS
  system usage stats:
        0.000002 elapsed 0.000001 user 0.000002 system sec
        [0.009993 user 0.049965 sys total]
        0/0 [0/1] filesystem blocks in/out
        0/0 [0/0] page faults/reclaims, 0 [0] swaps
        0 [0] signals rcvd, 0/0 [2/2] messages rcvd/sent
        0/0 [2/6] voluntary/involuntary context switches
  postgres usage stats:
        Shared blocks:          1 read,          0 written, buffer hit rate = 96.88%
        Local  blocks:          0 read,          0 written, buffer hit rate = 0.00%
        Direct blocks:          0 read,          0 written
```

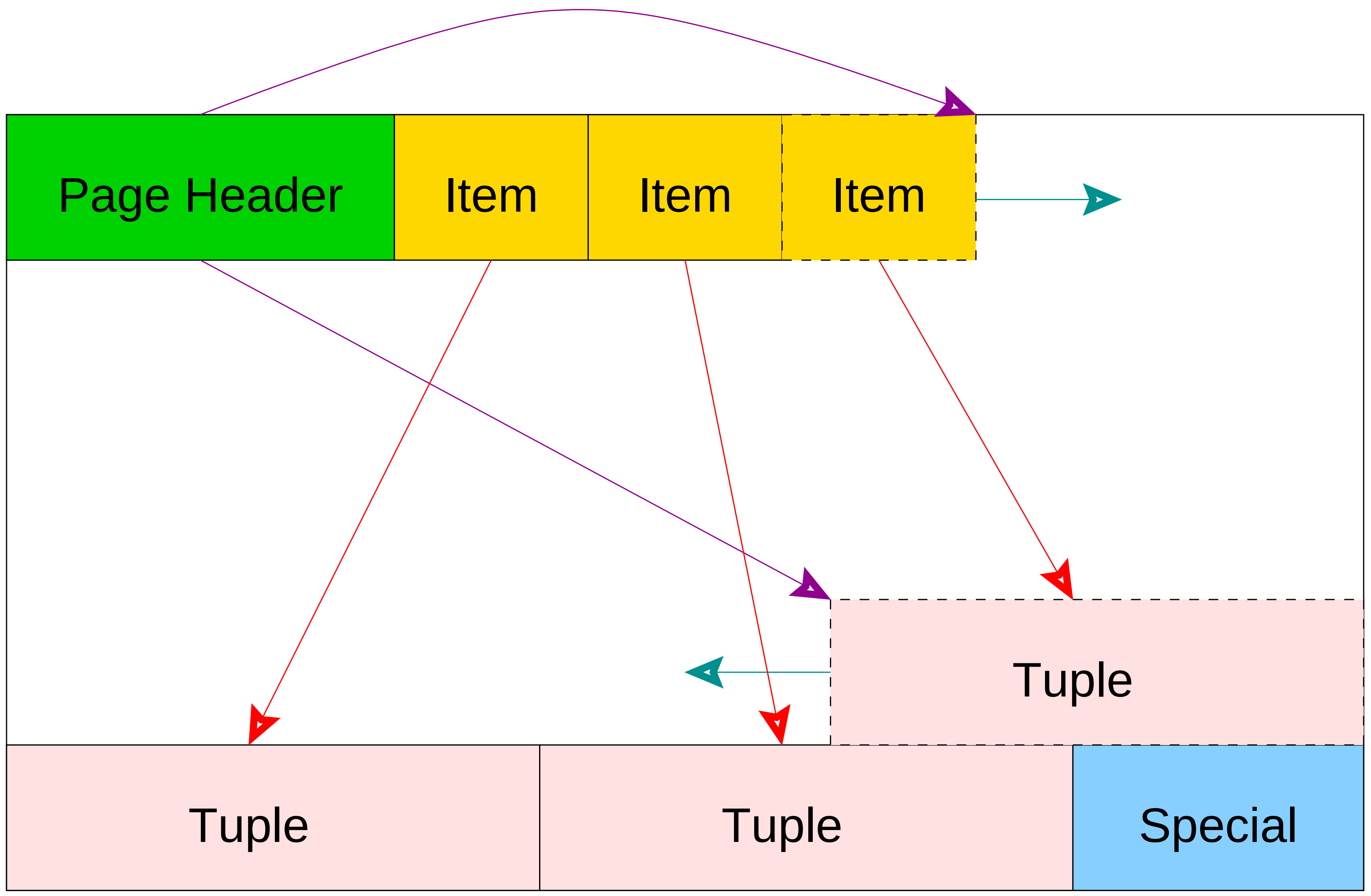
Statistics - Part 2

```
REWRITER STATISTICS
  system usage stats:
        0.000002 elapsed 0.000000 user 0.000002 system sec
        [0.009993 user 0.049968 sys total]
        0/0 [0/1] filesystem blocks in/out
        0/0 [0/0] page faults/reclaims, 0 [0] swaps
        0 [0] signals rcvd, 0/0 [2/2] messages rcvd/sent
        0/0 [2/6] voluntary/involuntary context switches
  postgres usage stats:
        Shared blocks:          0 read,          0 written, buffer hit rate = 0.00%
        Local  blocks:          0 read,          0 written, buffer hit rate = 0.00%
        Direct blocks:          0 read,          0 written
PLANNER STATISTICS
  system usage stats:
        0.009974 elapsed 0.009988 user -1.999985 system sec
        [0.019982 user 0.049955 sys total]
        0/0 [0/1] filesystem blocks in/out
        0/0 [0/0] page faults/reclaims, 0 [0] swaps
        0 [0] signals rcvd, 0/0 [2/2] messages rcvd/sent
        0/0 [2/6] voluntary/involuntary context switches
  postgres usage stats:
        Shared blocks:          5 read,          0 written, buffer hit rate = 96.69%
        Local  blocks:          0 read,          0 written, buffer hit rate = 0.00%
        Direct blocks:          0 read,          0 written
EXECUTOR STATISTICS
  system usage stats:
        0.040004 elapsed 0.039982 user 0.000013 system sec
        [0.059964 user 0.049970 sys total]
        0/0 [0/1] filesystem blocks in/out
        0/0 [0/0] page faults/reclaims, 0 [0] swaps
        0 [0] signals rcvd, 0/2 [2/4] messages rcvd/sent
        2/2 [4/8] voluntary/involuntary context switches
  postgres usage stats:
        Shared blocks:          2 read,          0 written, buffer hit rate = 83.33%
        Local  blocks:          0 read,          0 written, buffer hit rate = 0.00%
        Direct blocks:          0 read,          0 written
```

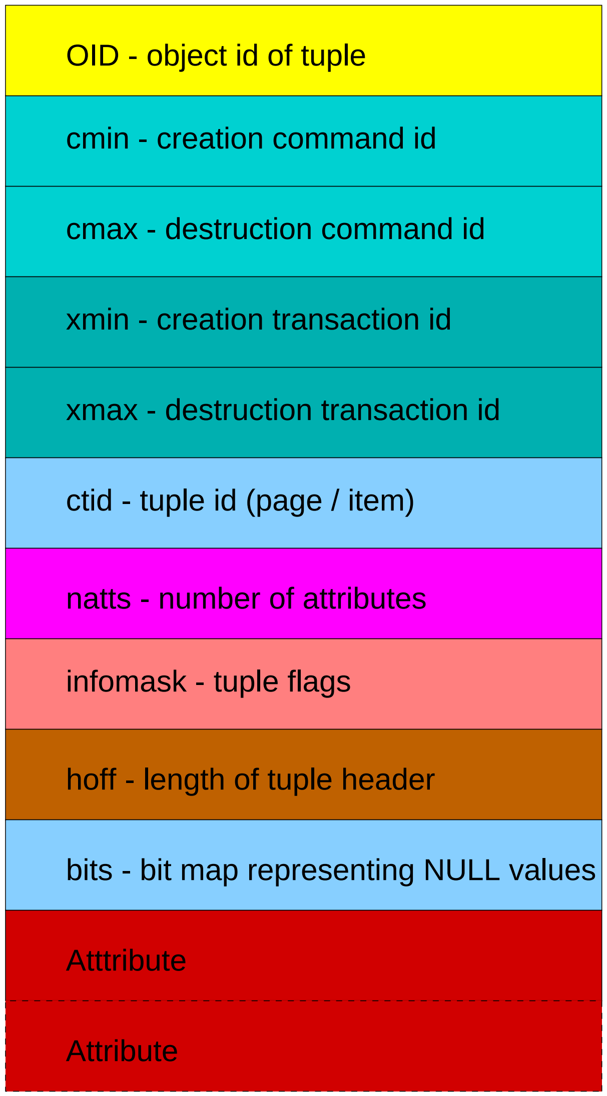
File Structure



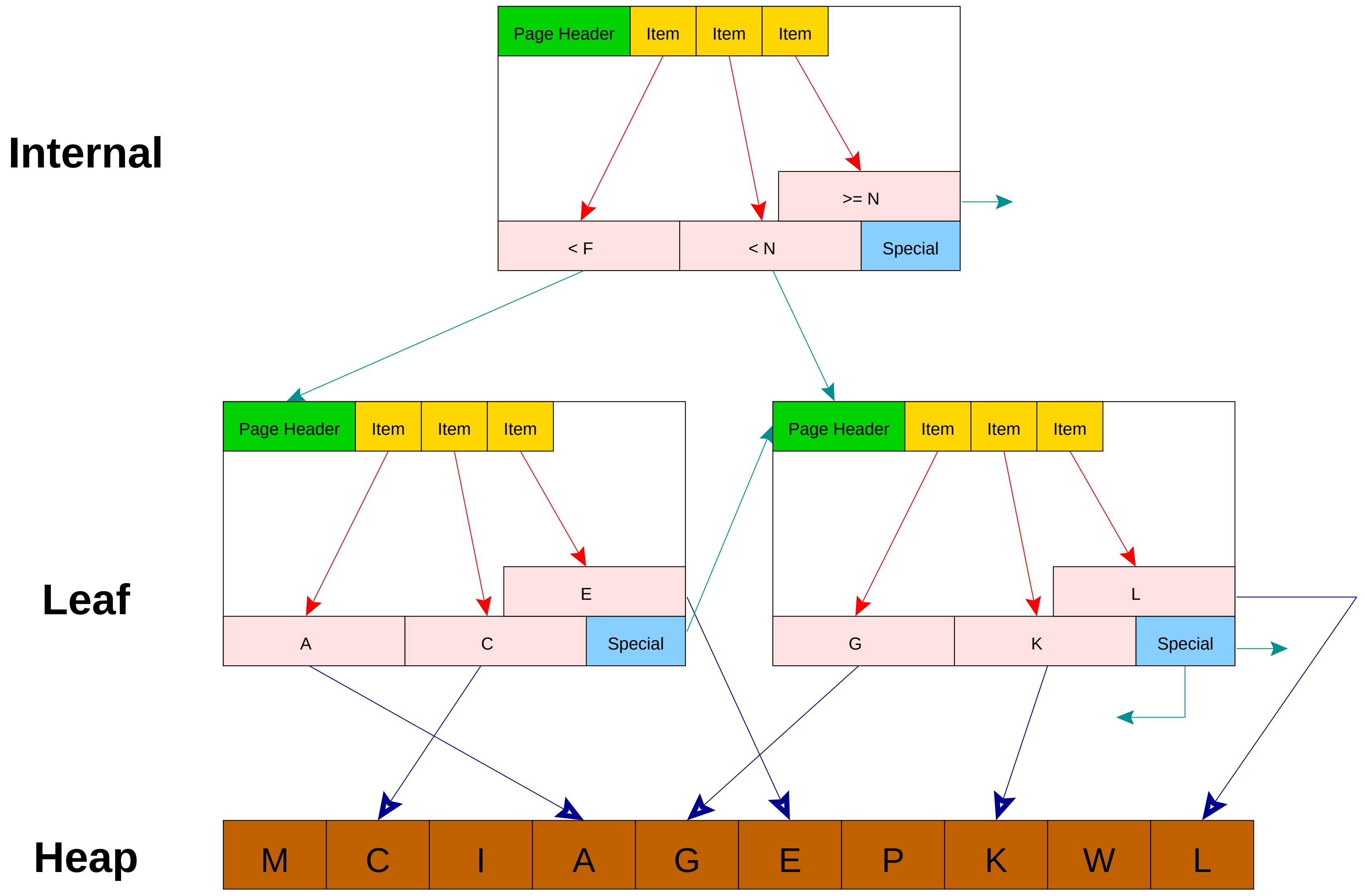
Page Structure



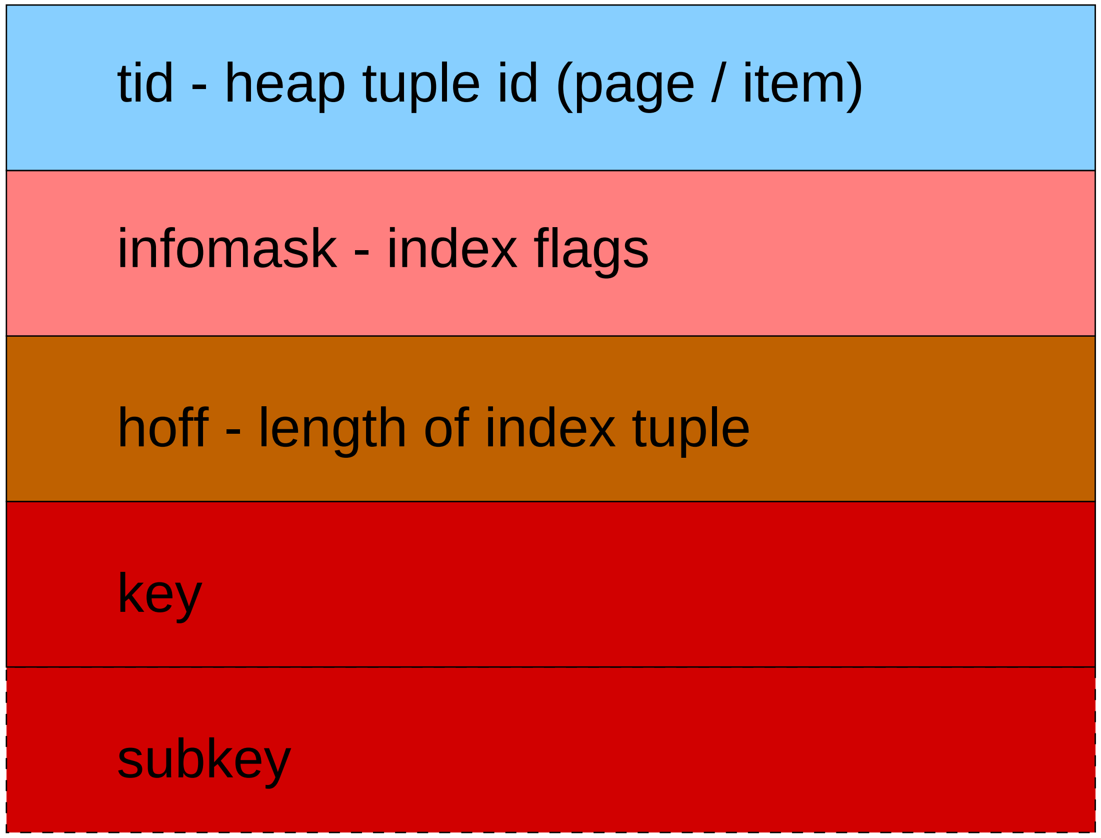
Heap Tuple Structure


OID - object id of tuple
cmin - creation command id
cmax - destruction command id
xmin - creation transaction id
xmax - destruction transaction id
ctid - tuple id (page / item)
natts - number of attributes
infomask - tuple flags
hoff - length of tuple header
bits - bit map representing NULL values
Atttribute
Attribute

Index Page Structure



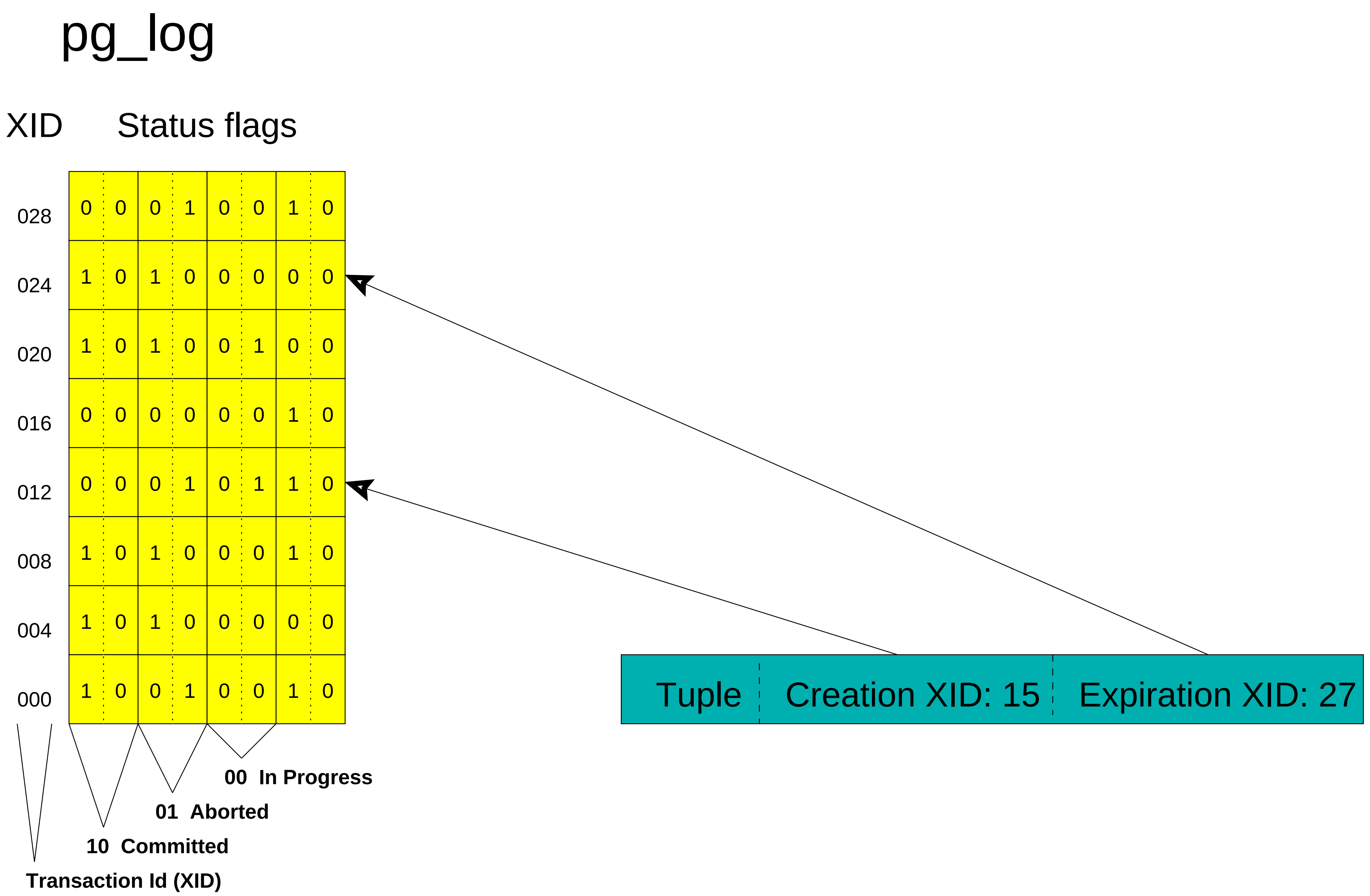
Index Tuple Structure


tid - heap tuple id (page / item)
infomask - index flags
hoff - length of index tuple
key
subkey

Index Types
(Access Methods)

- Btree
- Hash
- Rtree

Transaction Status



XID								
028	0	0	0	1	0	0	1	0
024	1	0	1	0	0	0	0	0
020	1	0	1	0	0	1	0	0
016	0	0	0	0	0	0	1	0
012	0	0	0	1	0	1	1	0
008	1	0	1	0	0	0	1	0
004	1	0	1	0	0	0	0	0
000	1	0	0	1	0	0	1	0

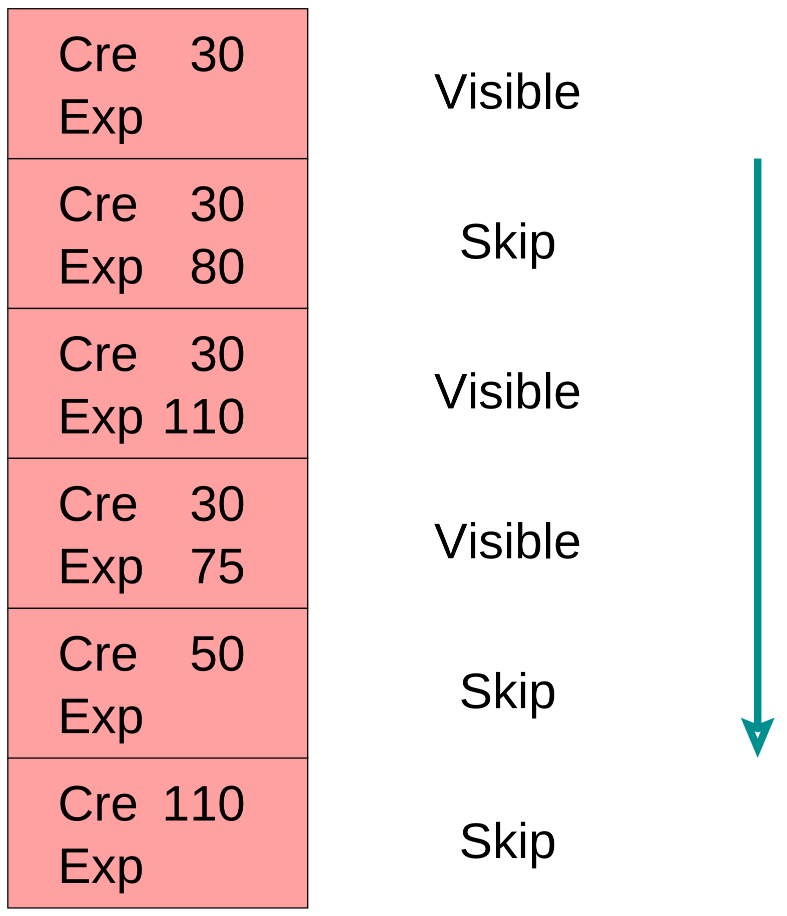
Multi-Version Concurrency Control

- Each query sees only transactions completed before it started
- On query start, PostgreSQL records:
  - the transaction counter
  - all transaction id’s that are in-process
- In a multi-statement transaction, a transaction’s own previous queries are also visible
- The above assumes the default *read committed isolation level*

MVCC Tuple Requirements

- Visible tuples must have a creation transaction id that:
  - is a committed transaction
  - is less than the transaction counter stored at query start *and*
  - was not in-process at query start
- Visible tuples must *also* have an expire transaction id that:
  - is blank *or* aborted *or*
  - is greater than the transaction counter stored at query start *or*
  - was in-process at query start

MVCC Example



Sequential Scan

Transaction Counter at query start: 100

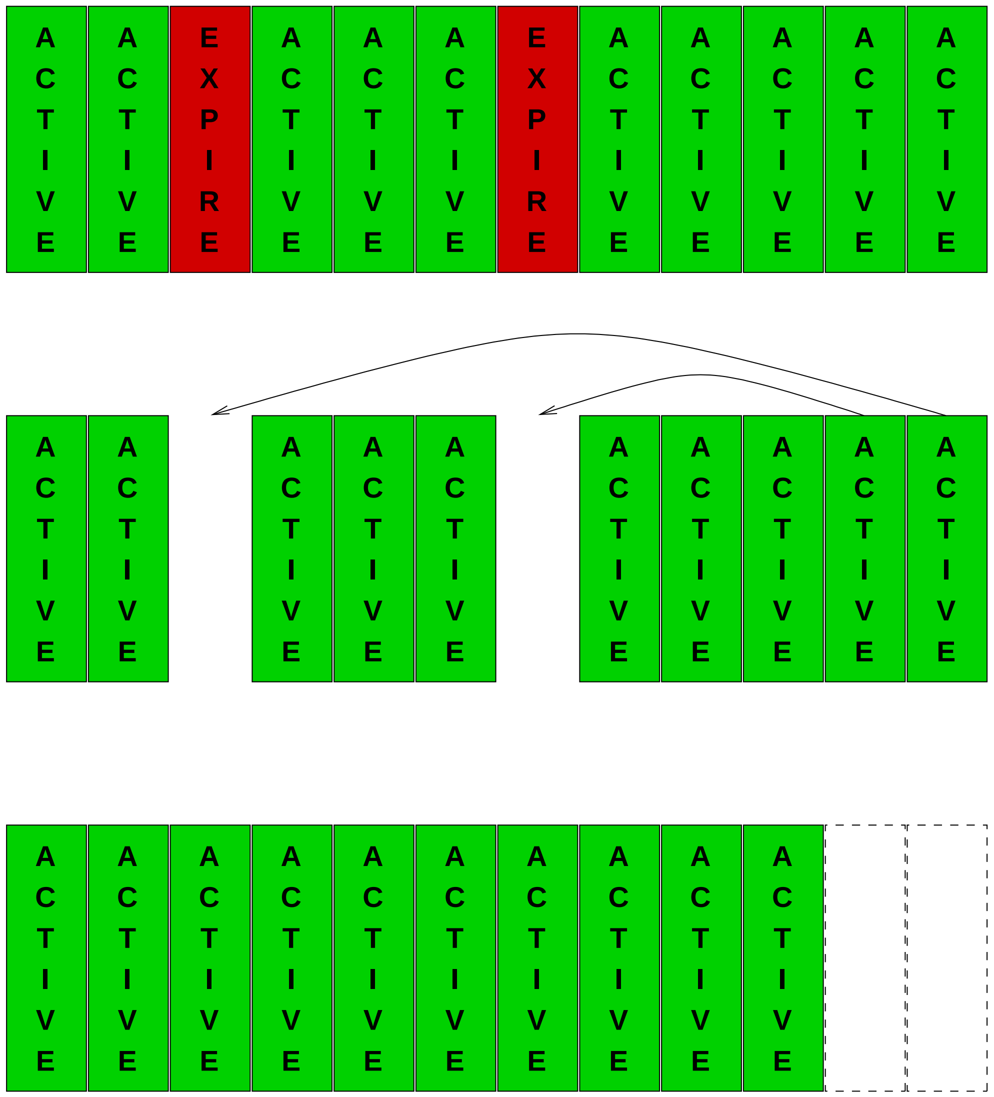
Open Transactions: 25, 50, 75

For simplicity, assume all other transactions are committed.

Snapshot Structure

```
typedef struct SnapshotData
{
    TransactionId xmin;          /* XID < xmin are visible to me */
    TransactionId xmax;          /* XID >= xmax are invisible to me */
    uint32      xcnt;            /* # of xact below */
    TransactionId *xip;          /* array of xacts in progress */
    ItemPointerData tid;         /* required for Dirty snapshot -:( */
} SnapshotData;
```

Vacuum



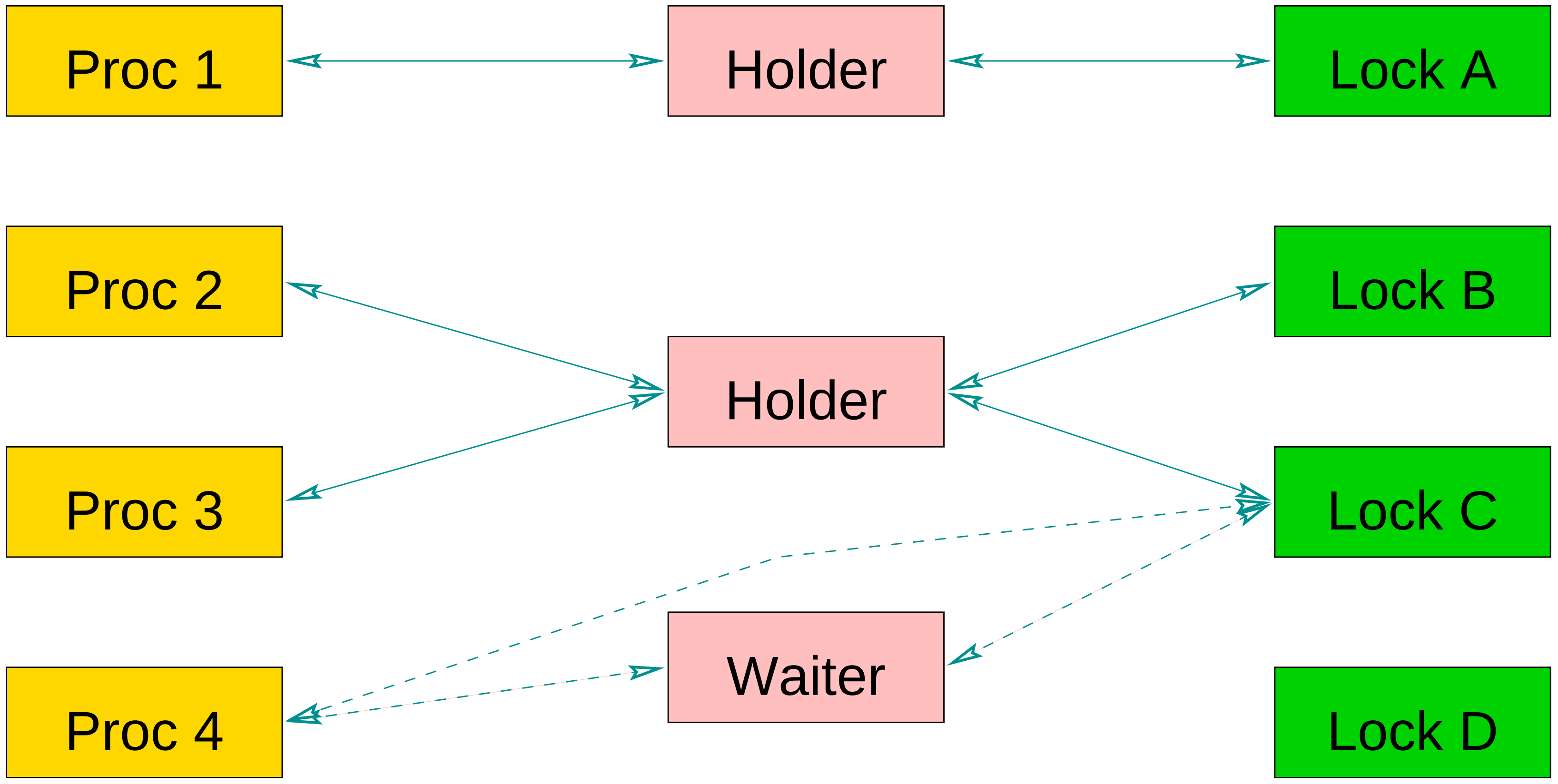
Proc Structure

```
struct proc
{
    /* proc->links MUST BE FIRST IN STRUCT (see ProcSleep,ProcWakeup,etc) */

    SHM_QUEUE   links;          /* list link if process is in a list */

    SEMA        sem;            /* ONE semaphore to sleep on */
    int         errType;        /* STATUS_OK or STATUS_ERROR after wakeup */

    TransactionId xid;          /* transaction currently being executed by
                                 * this proc */

    TransactionId xmin;         /* minimal running XID as it was when we
                                 * were starting our xact: vacuum must not
                                 * remove tuples deleted by xid >= xmin ! */

    XLogRecPtr  logRec;

    /* Info about lock the process is currently waiting for, if any. */
    /* waitLock and waitHolder are NULL if not currently waiting. */
    LOCK       *waitLock;       /* Lock object we're sleeping on ... */
    HOLDER     *waitHolder;     /* Per-holder info for awaited lock */
    LOCKMODE    waitLockMode;   /* type of lock we're waiting for */
    LOCKMASK    heldLocks;      /* bitmask for lock types already held on
                                 * this lock object by this backend */

    int         pid;            /* This backend's process id */
    Oid         databaseId;     /* OID of database this backend is using */

    short       sLocks[MAX_SPINS];      /* Spin lock stats */
    SHM_QUEUE   procHolders;    /* list of HOLDER objects for locks held or
                                 * awaited by this backend */
};
```

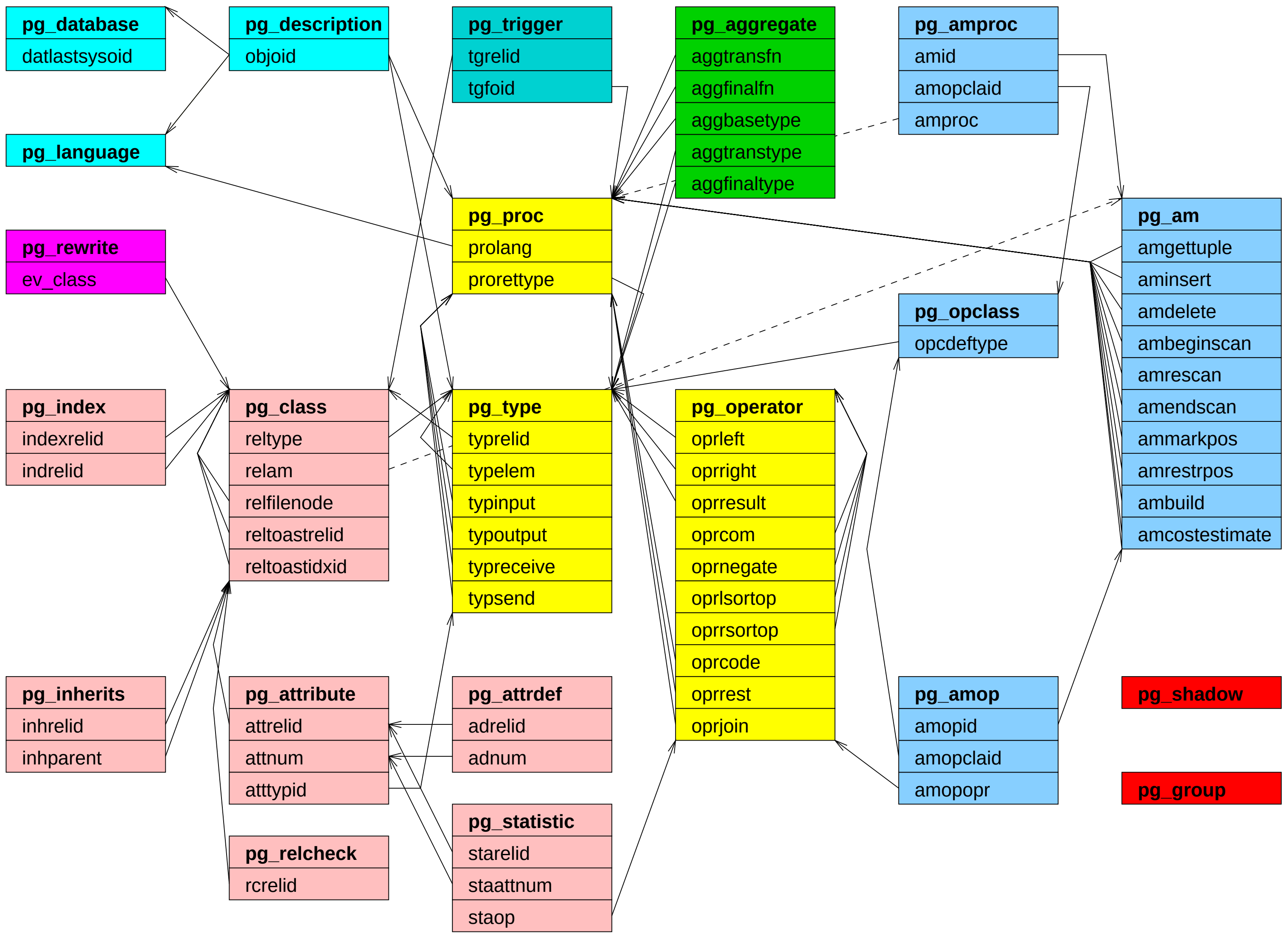
Lock Modes

Mode	Used
Access Share Lock	SELECT
Row Share Lock	SELECT FOR UPDATE
Row Exclusive Lock	INSERT, UPDATE, DELETE
Share Lock	CREATE INDEX
Share Row Exclusive Lock	EXCLUSIVE MODE but allows ROW SHARE LOCK
Exclusive Lock	Blocks ROW SHARE LOCK and SELECT...FOR UPDATE
Access Exclusive Lock	ALTER TABLE, DROP TABLE, VACUUM, and unqualified LOCK TABLE

Lock Structure



System Tables



Modifying System Capabilites

- CREATE FUNCTION
- CREATE OPERATOR
- CREATE TYPE
- CREATE LANGUAGE

Caches

- System Cache
- Relation Information Cache
- File Descriptor Cache

Shared Memory

- Proc structure
- Lock structure
- Buffer structure

Shared Buffers

```
typedef struct sbufdesc
{
    Buffer      freeNext;       /* links for freelist chain */
    Buffer      freePrev;
    SHMEM_OFFSET data;          /* pointer to data in buf pool */

    /* tag and id must be together for table lookup to work */
    BufferTag   tag;            /* file/block identifier */
    int         buf_id;         /* maps global desc to local desc */

    BufFlags    flags;          /* see bit definitions above */
    unsigned    refcount;       /* # of times buffer is pinned */

    slock_t     io_in_progress_lock; /* to block for I/O to complete */
    slock_t     cntx_lock;      /* to lock access to page context */

    unsigned    r_locks;        /* # of shared locks */
    bool        ri_lock;        /* read-intent lock */
    bool        w_lock;         /* context exclusively locked */

    bool        cntxDirty;      /* new way to mark block as dirty */

    BufferBlindId blind;        /* was used to support blind write */

    /*
     * When we can't delete item from page (someone else has buffer pinned)
     * we mark buffer for cleanup by specifying appropriate for buffer
     * content cleanup function. Buffer will be cleaned up from release
     * buffer functions.
     */
    void        (*CleanupFunc)(Buffer);
} BufferDesc;
```

Memory Routines

- palloc()
- pfree()
- MemoryContext's

Algorithms

Algorithm	Ordering	Lookup by Order	Insert	Delete	Lookup Insert/Del Recent	Pointers per Entry	Resize Overhead
list	insert	O(n)	O(1)	O(1)	O(1)	1-2	no
array	insert	O(1)	O(1)	O(n)	O(1)	~0.5	yes
tree	key	O(logN)	O(logN)	O(1)		2	no
array	key	O(logN)	O(n)	O(n)		~0.5	yes
hash	random	O(1)	O(1)	O(1)		~3	yes