SQL is a Programming Language

# Handwriting Recognition with SQL

and a tiny bit of web stuff

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## ABSTRACT

A basic handwriting recognition algorithm conceived in the 60's has been implemented, 50 years later, on top of a modern relational database system. We discuss the origins of the system, introduce the algorithm and its SQL implementation, provide a web app that captures pen strokes and sends them off to the database for processing, evaluate the approach and provide further context.

## 1 INTRODUCTION

Throughout the history of computing, human-computer interaction has been an ever-evolving avenue for research. The results of computations, in the early days indicated by blinking light bulbs, have more recently been presented on screens of ever-increasing resolution, with different output formats such as voice being explored continuously. On the input side of the equation, punch cards have given way to command prompts fed by keyboards, which in turn have largely been superseded touch- or voice-based user interfaces.

Both need to operate in lockstep: A fine meshing of input and output methods is required if an interface is to feel natural to users. Today's touch-based input devices, when compared to now-old-fashioned mouse input, exhibit clear usability upsides. Whenever the user wishes to manipulate a thing, she can simply touch it, instead of negotiating a mouse pointer towards it or entering keyboard shortcuts.

Current as this may be, it is not fundamentally new. More than 50 years ago, researchers at RAND Corporation came up with a pen-based input paradigm intended, according to GUI pioneer Alan Kay, "for economists and other non-computer specialists [...] who said 'Hey, none of us can type, can't you do something about that?'" [1] As part of this system, a basic handwriting recognition algorithm was developed. [2, 4]

**Outline.** Before delving into its details – and how a simplified variant of it, only able to recognize a single-stroke letter at a time (see figure 1), has been implemented as a SQL query – we will take a look at the RAND tablet and the GRAIL system it powers. After discussing the implementation, we will consider its performance and some related ideas.

## 2 GRAIL AND THE RAND TABLET

Developed by RAND in the 1960s, the Graphic Input Language (GRAIL) was a flowchart-based programming system. [7] As described by its creators, it enables a user to "draw flowchart symbols,

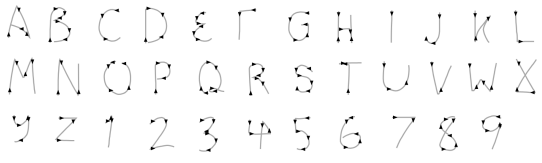


**Figure 1: How to draw the simplified characters.**

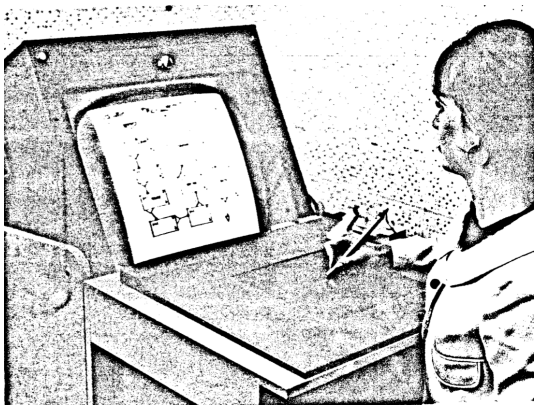


**Figure 2: A scan [7] of a printout of a photograph of a user interacting with GRAIL.**

edit and rearrange them on the display surface, and connect them appropriately to form a meaningful program. [The user can] execute the program while controlling its execution rate and the amount and content of information presented to him. The system interprets, in real-time, the [user's] hand-drawn figures, characters, and other [...] gestures to provide germane responses on the display surface." [6] Alan Kay, in a talk where he demonstrates GRAIL, summarizes it as "the world's first modeless system" and notes that it is "where Macintosh window control came from" [1].

The user operated the GRAIL system using a stylus connected to a tablet as shown in figure 2. Its "writing surface is a 10"x10" area with a resolution of 100 lines per inch in both x and y [...], allowing the user to 'write' in a natural manner. [...] To maintain 'naturalness' of the pen device, a pressure-sensitive switch in the tip of the stylus indicates 'stroke' [...] to the computer" [5].[1]

The original "IBM/360 assembly language program for online graphical-input character recognition using the RAND Tablet" [3] is publicly available, but was not consulted when writing the SQL query – it is too low-level to be of much utility.

### 2.1 Web app

Testing the SQL query necessitates a simple simulation of the RAND tablet, which was given along with the assignment in the form of a D3.js-based web app that prints a list of coordinates once the user draws a character.

In order to present the algorithm succinctly, this was extended with a server component that, with the help of some Python code, dynamically executes the handwriting recognition query on a Postgres instance and returns the result to the user.[2]

[1] The authors of this memo describe the function of the tablet in great detail. Another memo takes a deep dive into the innards of GRAIL. [8]

[2] This is given in `code/index.html`. The backend setup is a can of worms, so it's recommended to just use the frontend, which yields a JSON version of the pen stroke.

```
1  WITH RECURSIVE
2  tablet(pos, x, y) -- ... (conversion of JSON list to rows)
3  smooth(pos, x, y) AS (
4    SELECT pos, x :: real, y :: real FROM tablet WHERE pos = 1
5      UNION ALL
6    SELECT t.pos,
7           (:smoothingfactor * s.x + (1.0 - :smoothingfactor) * t.x) :: real AS x,
8           (:smoothingfactor * s.y + (1.0 - :smoothingfactor) * t.y) :: real AS y
9    FROM   smooth s, tablet t
10   WHERE  t.pos = s.pos + 1
11 ),
12 thin(pos, x, y) AS (
13   SELECT * FROM smooth WHERE pos = 1
14     UNION ALL
15   SELECT *
16   FROM   (
17     SELECT s.pos, s.x, s.y
18     FROM   thin t, smooth s
19     WHERE  s.pos > t.pos
20     AND    :thinningsize < |/ (s.x - t.x)^2 + (s.y - t.y)^2
21     ORDER BY s.pos
22     LIMIT 1
23   ) AS _
24 ),
25 curve(pos, x, y, direction) AS (
26   SELECT pos, x, y,
27          COALESCE(degrees(-atan2( y - lag(y) OVER (ORDER BY pos),
28                                  -x + lag(x) OVER (ORDER BY pos))
29                           ) + 180, 90)
30   FROM   thin
31 ),
32 cardinal(pos, direction) AS (
33   SELECT pos,
34          (enum_range(NULL :: cardinal_direction))[(direction / 90) :: int % 4 + 1]
35   FROM   curve
36 ),
37 cardinal_change(pos, direction) AS (
38   SELECT pos, direction
39   FROM   (SELECT pos, direction,
40                  COALESCE(lag(direction, 2) OVER win <> lag(direction) OVER win,
41                           true)
42                  AND lag(direction) OVER win = direction
43           FROM cardinal
44           WINDOW win AS (ORDER BY pos)) AS _(pos, direction, is_new)
45   WHERE  is_new
46 ),
47 corner(pos, x, y) AS (
48   SELECT pos, x, y
49   FROM   (SELECT pos, x, y, (
50                     angdiff(lag(direction, 2) OVER win, lag(direction) OVER win) < 22.5
51                     AND angdiff(lag(direction) OVER win, direction) > :cornerangle
52                     AND angdiff(direction, lead(direction) OVER win) < 22.5
53                   ) OR (  -- Immediate direction change OR one-segment turn.
54                     angdiff(lag(direction, 3) OVER win, lag(direction, 2) OVER win) < 22.5
55                     AND angdiff(lag(direction, 2) OVER win, direction) > :cornerangle
56                     AND angdiff(direction, lead(direction) OVER win) < 22.5
57                   ) AS is_corner
58           FROM   curve
59           WINDOW win AS (ORDER BY pos)) AS _(pos, x, y, is_corner)
60   WHERE  is_corner
61 ),
62 aabb(xmin, xmax, ymin, ymax, aspect, width, height, centerx, centery) -- ...
63 start_grid(n) AS (
64   SELECT gridpos(a.width, a.height, a.xmin, a.ymin, s.x, s.y)
65   FROM   smooth s, aabb a
66   ORDER BY s.pos
67   LIMIT 1
68 ),
69 stop_grid(n) -- ... (analogous to start_grid)
70 corner_grid(pos, n) -- ... (also similar)
71 features(directions, start, stop, corners, width, height, aspect, center) AS (
72   SELECT (SELECT array_agg(direction ORDER BY pos)
73           FROM   cardinal_change),
74          (TABLE start_grid),
75          (TABLE stop_grid),
76          (SELECT COALESCE(array_agg(n ORDER BY pos), '{}')
77           FROM   corner_grid),
78          width, height, aspect, point(centerx, centery)
79   FROM   aabb
80 ),
81 character(character) AS (
82   SELECT l.character
83   FROM   features f, lookup_candidates c, lookup_bestfit l
84   WHERE  f.directions[1:4] = c.first_four_directions
85   AND    c.candidate_characters = l.candidate_characters
86   AND    (l.start IS NULL          OR f.start = l.start)
87   AND    (l.stop IS NULL           OR f.stop = l.stop)
88   AND    (l.corners IS NULL        OR f.corners = l.corners)
89   AND    (l.aspect_range IS NULL   OR l.aspect_range @> f.aspect :: numeric)
90 )
91 TABLE character;
```

**Figure 3: Slightly condensed SQL implementation. Some custom functions have been omitted.**

# 3 IMPLEMENTATION

The web app outputs a JSON value of the form `[{"x": 37, "y": 39}, {"x": 38, "y": 43, ...}]`. It is passed to the Postgres[3] command-line client `psql` and converted to a table with an sequantial identifier column in CTE `tablet` (see figure 3).

## 3.1 Smoothing & Thinning

The RAND tablet provides a stream ("the recognition scheme is notified of [the pen] position every 4 msec" [2]) of pen positions as integer $x, y$ coordinate pairs.

As a preprocessing step, this digital representation pen stroke is smoothed to counteract quantization effects ("noise due to the discreteness of the pen location as measures by the tablet" [2], which can negatively affect later steps of the algorithm) as shown in figure 4. Smoothing is performed by computing a weighted average of the most recently smoothed point (weight 75%; the first point of the stroke is assumed to be smooth already) and the next incoming point ( 25%). In SQL, this is accomplished by the recursive CTE `smooth` where the weight is stored in the `psql` variable `smoothingfactor`.

The second stage of preprocessing drops points that are in close proximity to a previous point and thus contribute little or no additional information. This mainly serves to ease the computing effort required during the next stages. Groner uses a set of inequalities that compare $x$ and $y$ positions, effectively superimposing a square over each point and removing any other points that fall into this square. This is less "correct" than pruning based on the Euclidean distance as implemented in the SQL query (line 20), but computationally more efficient. The seemingly superfluous wrapping for the recursive part of the `thin` CTE in a `SELECT * FROM (...) AS _` is required because Postgres does not permit `ORDER BY` directly in a recursive query.

The degree to which these steps affect the raw data is controlled using the `psql` variables `smoothingfactor` and `thinningsize`. Choosing sensible values is important: As `smoothingfactor` approaches 1, corners disappear and the end of the stroke is pulled closer to the start. This effect is visible in figure 4 where ●● extend further along the $x$ axis than ●●. Similarly, a large `thinningsize` can obscure corners or bends in the stroke.

[3] Postgres 9.4 or newer is required.

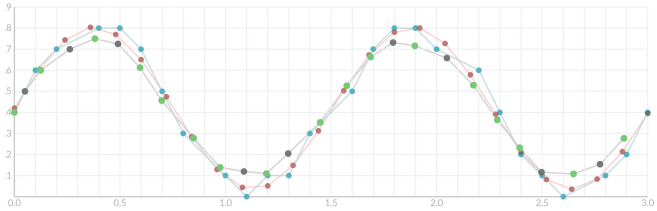



**Figure 4: The ● pen stroke drawn by the user, the corresponding ● quantized signal received by the computer, the ● smoothed intermediate result and ● the points left after thinning.**

## 3.2 Curvature

"Curvature is the most obvious characteristic which is independent of position and size, and yet which describes the [stroke]'s shape. [...] Four directions, used in conjunction with other features, provide sufficient description for recognition, yet result in [less effort] than do [more] directions." [2] Only changes of these cardinal directions the pen stroke moves toward as each character is drawn are kept.

Groner extracts this feature by comparing positional differences of point pairs using a set of inequalities. Because more fine-grained curvature information is helpful in detecting corners later on, the SQL implementation (see CTE `curve`) instead computes the precise angle between the line connecting each pair of points and the $x$ axis as shown in figure 5.

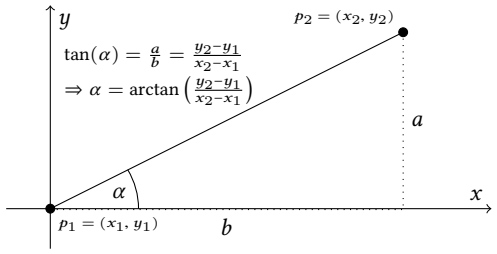



**Figure 5: Deriving the angle $\alpha$ between two points $p_1$ and $p_2$.**

In CTE `cardinal` it is then quantized to determine the cardinal directions, denoted by an `ENUM` type comprising the Unicode symbols ▲▼◀▶. To accomplish this, the `enum_range(anyenum)` function is used, which returns all values of the input enum type as an array.[4]

"If the same direction occurs twice in succession, and is not the same as the last direction [...], then it is added to the [result], otherwise it is discarded." [2] Thus the CTE `cardinal_change` takes care of discarding sequential duplicates.

TODO because window functions cannot be used in where, an awkward subquery todo "They are forbidden elsewhere, such as in `GROUP BY`, `HAVING` and `WHERE` clauses. This is because they logically execute after the processing of those clauses." [5]

## 3.3 Corners

Cardinal directions are sufficient to discern between many characters, but in some cases – see figure 6a – other features such as the presence or absence of corners are required. "A corner is detected whenever the pen moves in the same (±1) 16-direction for at least two segments [▶▶], changes direction by at least 90°, and then proceeds along the new direction (±1) for at least two segments [▶▶]. The change in direction must take place either immediately or through a one-segment turn [▶]." [2] (The triangles correspond to the lower half of figure 6a.)

Instead of 16-directions (*i.e.*, the division of 360° into 16 slices), the CTE `corner` of the SQL implementation uses absolute angles, making sure that the two line segments directly before a corner point within $\frac{360°}{16} = 22.5°$ of each other, the two next line segments also point within 22.5° of each other and the angle at the corner point is > 90°. The window function `lag()` is used to access previous and next points – rather, the angles the associated line segments point towards – and a custom `angdiff()` function computes the delat

$$\arctan\left(\frac{\sin(\alpha - \beta)}{\cos(\alpha - \beta)}\right)$$

between a pair of angles.[6] The output of the CTE is a table of corner positions.

## 3.4 Additional features

In addition to cardinal directions and corners, Groner's algorithm determines a number of additional features: "the symbol's height and width [...], its aspect ratio [...], and its center relative to the tablet origin." [2] They are of limited use to the simplified single-stroke alphanumeric characters supported by the SQL implementation; *e.g.*, height and width aid in discerning parentheses from commata.

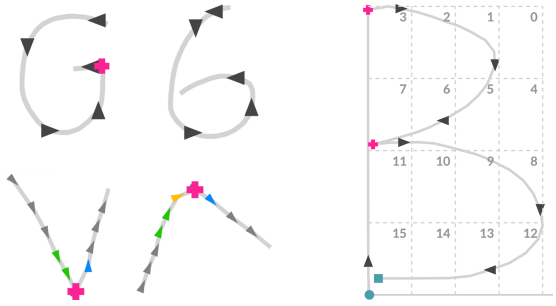
Nevertheless, they are extracted in the CTE `aabb`, which trivially derives an axis-aligned bounding box around the character drawn by the user and returns two $x, y$ pairs defining it, along with width, height, center and aspect ratio.

**Grid.** The algorithm then "divides the rectangular area defined by the symbol into a 4 x 4 grid. The starting (pen-down) and ending (pen-up) points, as well as the corner locations, are then each encoded as lying in one of these 16 areas, thereby locating them relative to the symbol." [2] Figure 6b shows an example.

The SQL implementation uses a custom `gridpos(width, height, xmin, ymin, x, y)` function which "desugars" to an arithmetic expression mapping `x` and `y`, given an AABB defined by minimum x, y, `width` and `height` to grid positions.[7]

Finally, the CTE `features` combines all extracted features into a single-row table.

[4] See https://www.postgresql.org/docs/8.3/static/functions-enum.html.
[5] See https://www.postgresql.org/docs/10/static/tutorial-window.html.
[6] See https://stackoverflow.com/a/2007279. The formula $180 - ||\alpha - \beta| - 180|$ is equivalent and cheaper to compute, but the one given in the text elegantly combines sin, cos and (arc)tan.
[7] Global state would be convenient here to avoid passing the unchanging AABB on each call, but creating an extra temporary table for storing it seems like overkill.




**(a) Corners help discern between similar charachters. They are determined based on the angles between four to five successive line segments.**

**(b) The absolute positions of corners, as well as start and end of a stroke are converted to grid positions.**

**Figure 6: Cardinal directions, corners and the grid.**

### 3.5 Mapping Features to Characters

The

TODO decision tree, not relational, most challenging portion of the work (rest smooth sailing)

**Alternate approaches.** TODO benjamin's idea worse because * 4-direction patterns in the first lookup table that map to a *single* character essentially skip the second lookup table (see 'INSERT' in line 116 of the setup file). This could be somehow emulated using a query (if 'COUNT(candidate_character)' for the current pattern is 1, skip the feature-matching step), but that adds cruft to the query. * Deciding between 7 and 1 requires features F, while deciding between 7 and 3 requires looking at features G != F. Could also be patched over at the query level. * More verbose first lookup table, slimmer second lookup table. * Second lookup table does not anymore indicate which 4-direction pattern a given feature match belongs to, making debugging/extending harder. * Effectively requires ranking results based on closeness of match, e.g. number of features used (or VERY careful design of the second lookup table, which I didn't have time for before my presentation). * Conceptually further from original tree structure, which can be a bad or good thing.

## 4 EVALUATION

Basing his analysis on the original IBM/360 assembly program running on a Model 40, Groner writes that the preprocessing and feature extraction stage "takes up about 40 percent of the available computing time in the limiting case [...]. Smoothing and thinning requires about 20 percent of this analysis time, [drawing each incoming segment to the screen] 30 percent, and corner detection 16 percent. The remainder of the analysis time is for computing quantized directions, updating x and y extremes, and bookkeeping." He goes on to outline potential improvements that could cut the computing time down to "only about 15 percent" [2]. TODO nothing about decision tree performance, probably quite fast

TODO groner's user tests

Profiling the web version and SQL query is a bit more difficult TODO EXPLAIN analyze, compare to groner's breakdown, should roughly correspond

## 5 RELATED & FUTURE WORK

**Related work.** TODO that moto? input thingy

TODO dynamic time warping, see denis and http://www.hcii-lab.net/lianwen/Papers/Conference/

TODO get the apple newton into this

**Future work.** TODO improvements: multiple strokes, changes to make thing more suited to modern stuff (no smoothing/thinning due to higher (scan) resoltion of current tech), better representation of decision tree (perhaps more elegant on a graph db, but really no expert, heh)

TODO some discussion on this approach, with multiple strokes support, being particularly suited for CJK input due to rigidly defined stroke order even though characters can look a bit complex, and indeed this has been done before https://www.rand.org/pubs/papers/P3568.html

## 6 CONCLUSION

TODO whatever, maybe drop

## REFERENCES


[1] Alan Kay. Doing with Images Makes Symbols: Communicating with Computers. http://archive.org/details/AlanKeyD1987?start=1439.5, 1987 (uploaded to archive.org in 2002, accessed August 10, 2018).

[2] Gabriel F. Groner. *Real-Time Recognition of Handprinted Text.* RAND Corporation, Santa Monica, CA, 1966.

[3] Gabriel F. Groner. *Real-Time Recognition of Handprinted Text: Program Documentation.* RAND Corporation, Santa Monica, CA, 1968.

[4] Jack Schaedler. Back to the Future of Handwriting Recognition. https://jackschaedler.github.io/handwriting-recognition/, 2016 (accessed August 10, 2018).

[5] Malcolm Davis and T. O. Ellis. *The RAND Tablet: A Man-Machine Graphical Communications Device.* RAND Corporation, Santa Monica, CA, 1964.

[6] T. O. Ellis, J. F. Heafner, and W. L. Sibley. *The GRAIL Language and Operations.* RAND Corporation, Santa Monica, CA, 1969.

[7] T. O. Ellis, J. F. Heafner, and W. L. Sibley. *The Grail Project: An Experiment in Man-Machine Communications.* RAND Corporation, Santa Monica, CA, 1969.

[8] T. O. Ellis, J. F. Heafner, and W. L. Sibley. *The GRAIL System Implementation.* RAND Corporation, Santa Monica, CA, 1969.