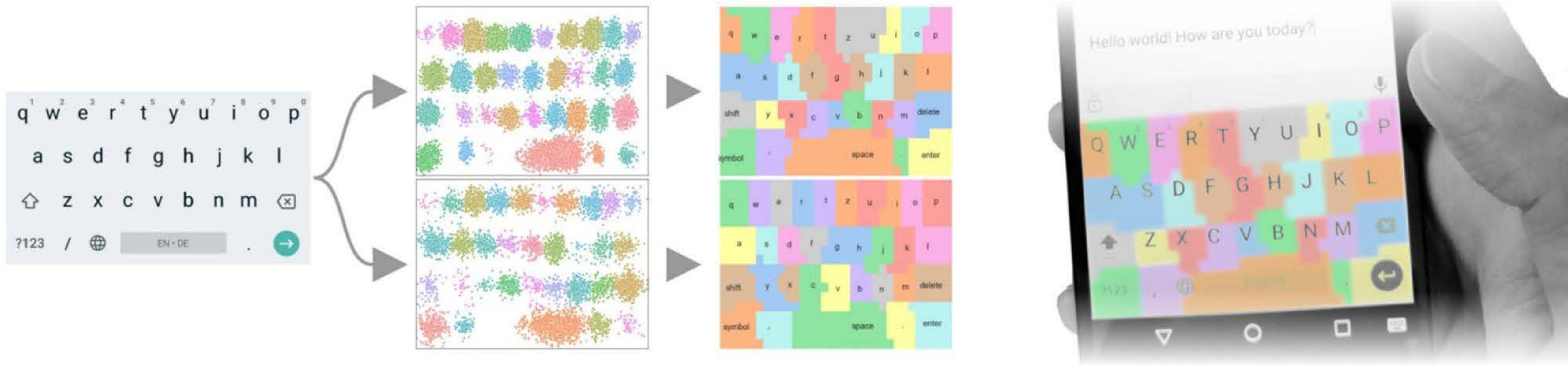


Intelligent Text Input and Optimization

Learning Goals

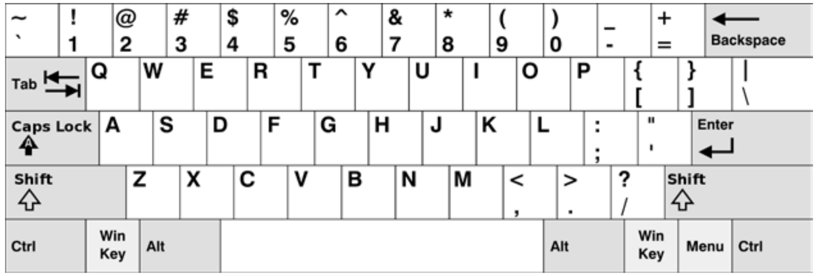
- Combinatorial optimization as a UI design approach
- Probabilistic methods for handling input
- Application example: keyboards

Optimizing User Interfaces

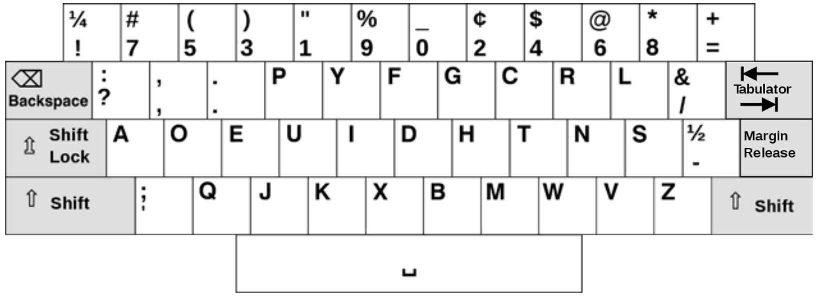
Example: keyboard layout optimization

Motivation: Fast typing without errors

- Are some layouts better than others?
- If so, how do we find the best one?



QWERTY, by Christopher Sholes, 1873



Dvorak, by August Dvorak, 1936

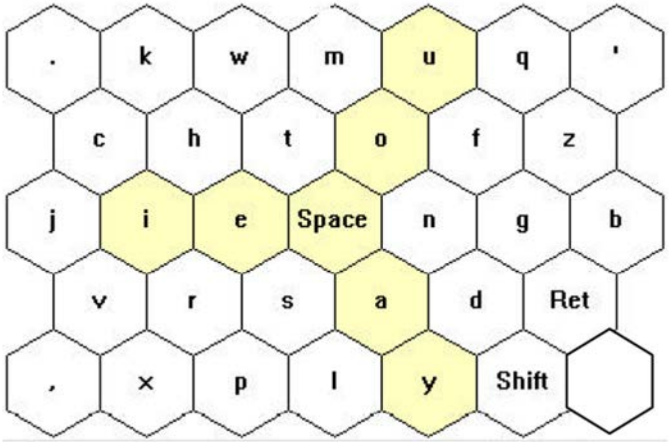
By: https://commons.wikimedia.org/wiki/File:KB_United_States.svg, https://commons.wikimedia.org/wiki/File:KB_United_States_Dvorak.svg

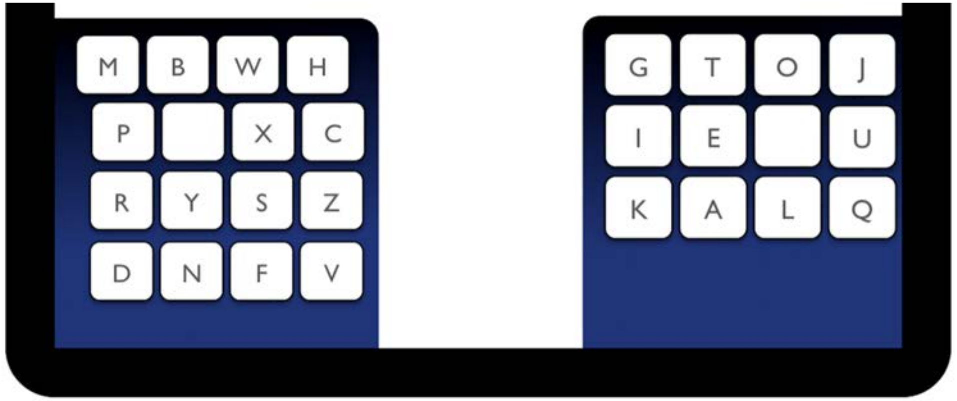
Key Assignment Problem

How many layouts are there? **26! = 4 * 10^{26}**

For comparison - stars in the universe: https://www.esa.int/Science_Exploration/Space_Science/Herschel/How_many_stars_are_there_in_the_Universe

Examples of Optimised Designs





Zhai et al. 2000, Dunlop and Levine 2012, Oulasvirta et al. 2013, Gong et al. 2018

What is „optimal“?

- **Design space:**
  Best among which options?

- **Design objective:**
  Best for what?

- **Optimizer:**
  How to find the best design?
  Best with which guarantees?

Design Space, formalised

$$d = \begin{pmatrix} d_1 \\ d_2 \\ \vdots \\ d_n \end{pmatrix}$$

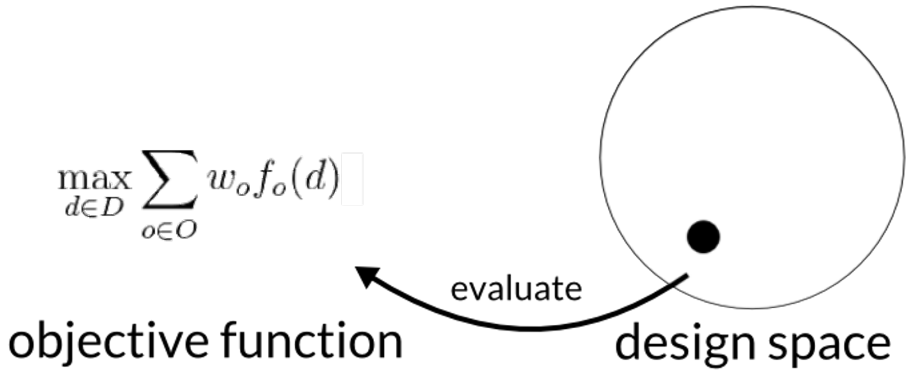
Design space ***D***
with ***n*** design variables

Design Space: Set of possible layouts

$$26! = 4 * 10^{26}$$

design space

Objective Function: How to judge a layout?



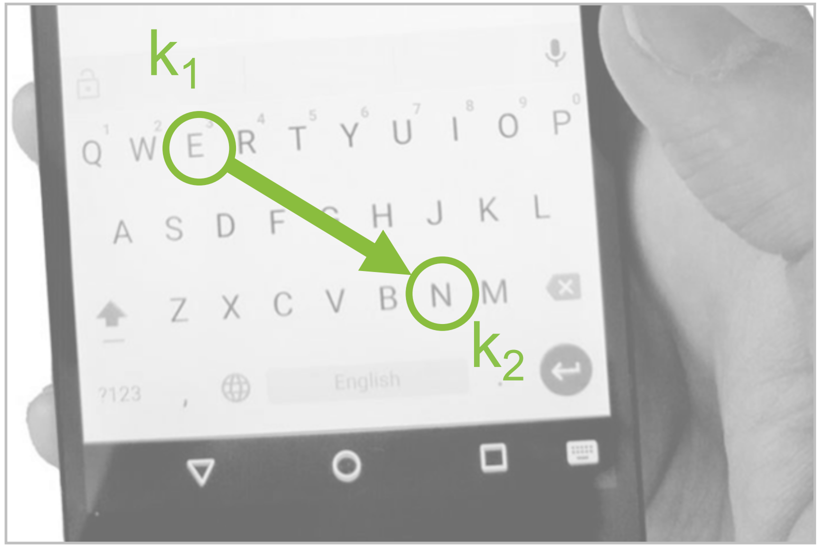
Objective Function: How to judge a layout?

- Finger movement time (e.g. Fitts' law)

$$t(k_1, k_2) = a + b\log_2\left(\frac{D}{W} + 1\right)$$

- Language properties (e.g. bigram frequencies)

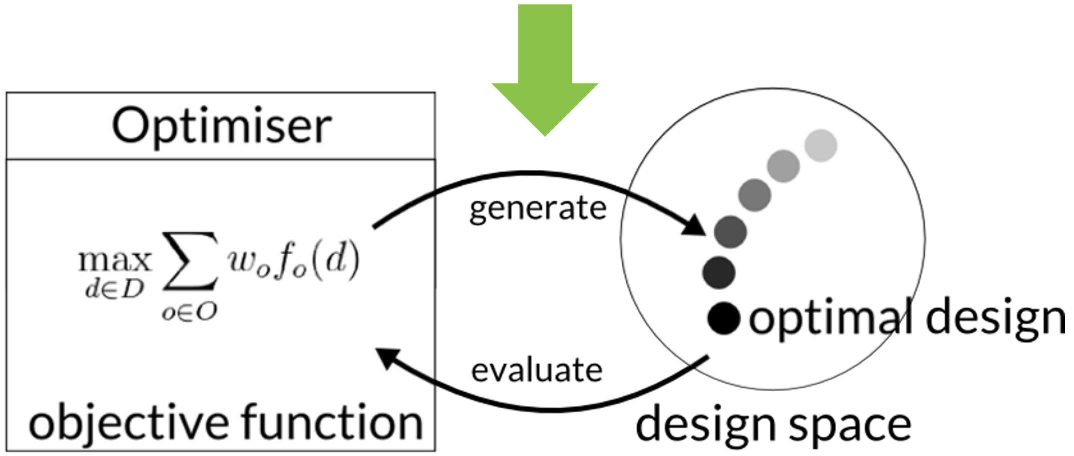
e.g. $p(\text{"}n\text{"}|\text{"}e\text{"}) = 0.001$



- Combined: mean time between two key presses

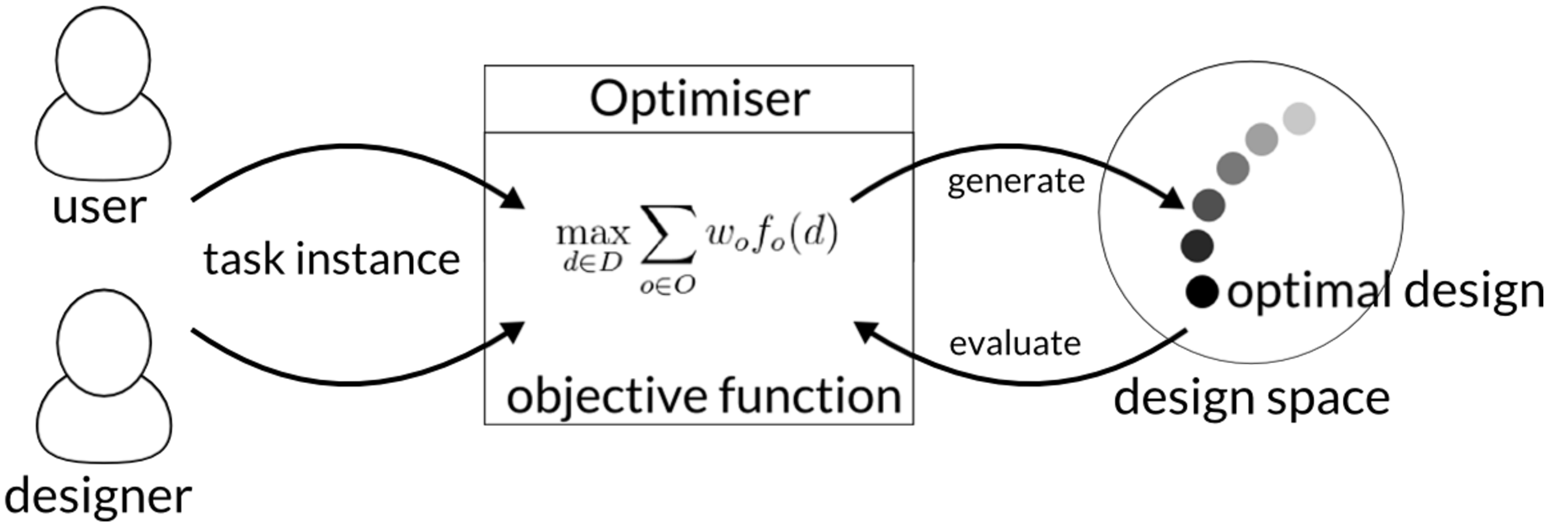
$$f(d) = \sum_{k_1 \in K} \sum_{k_2 \in K} p(d(k_2)|d(k_1))t(k_1, k_2) \quad \text{where the design } d \text{ maps from keys to characters}$$

Optimizer: How to pick layouts?



Design Task

e.g. keyboard layout optimization



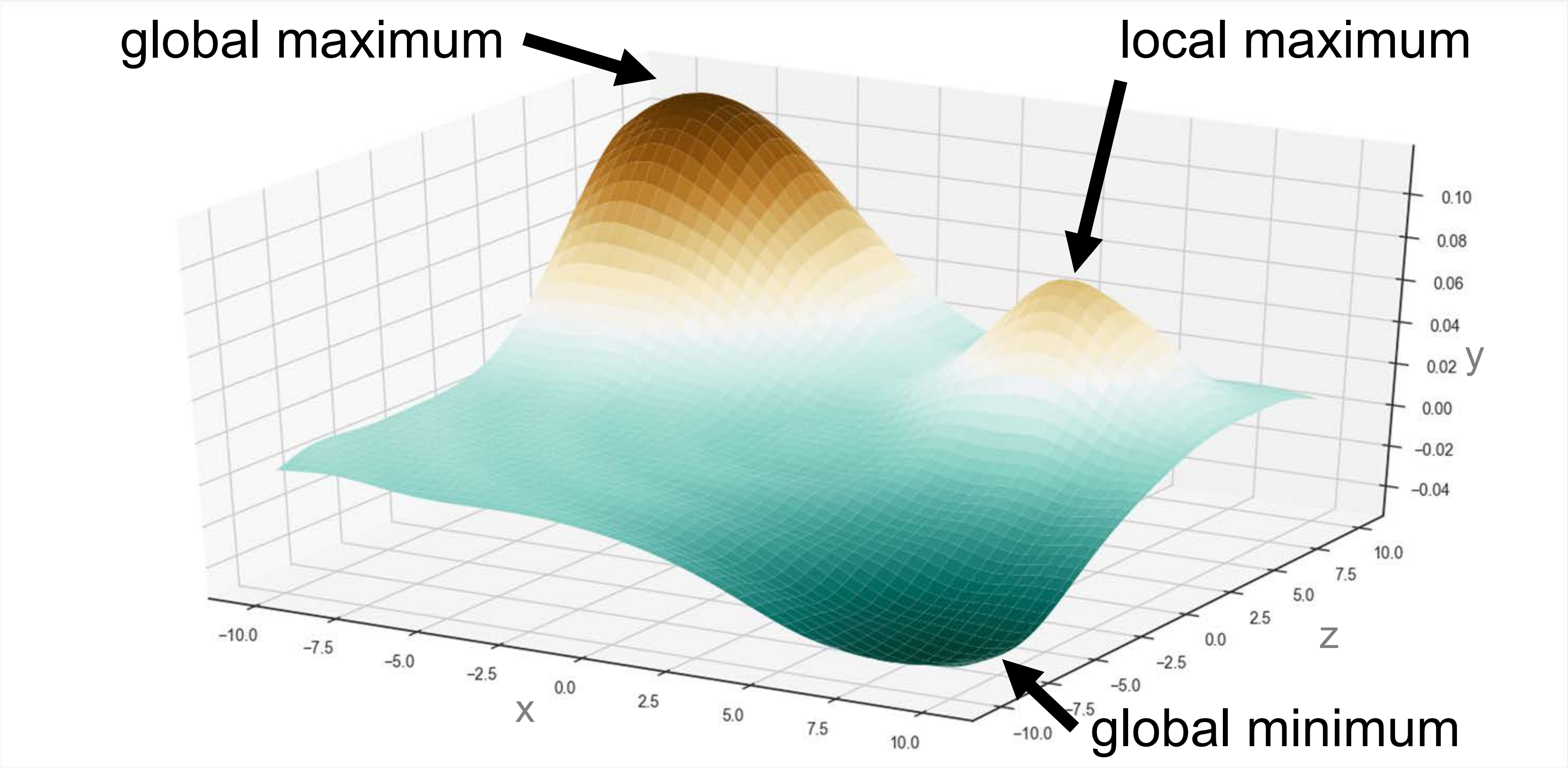
A Simple Optimizer

- Can you think of a trivial optimizer?

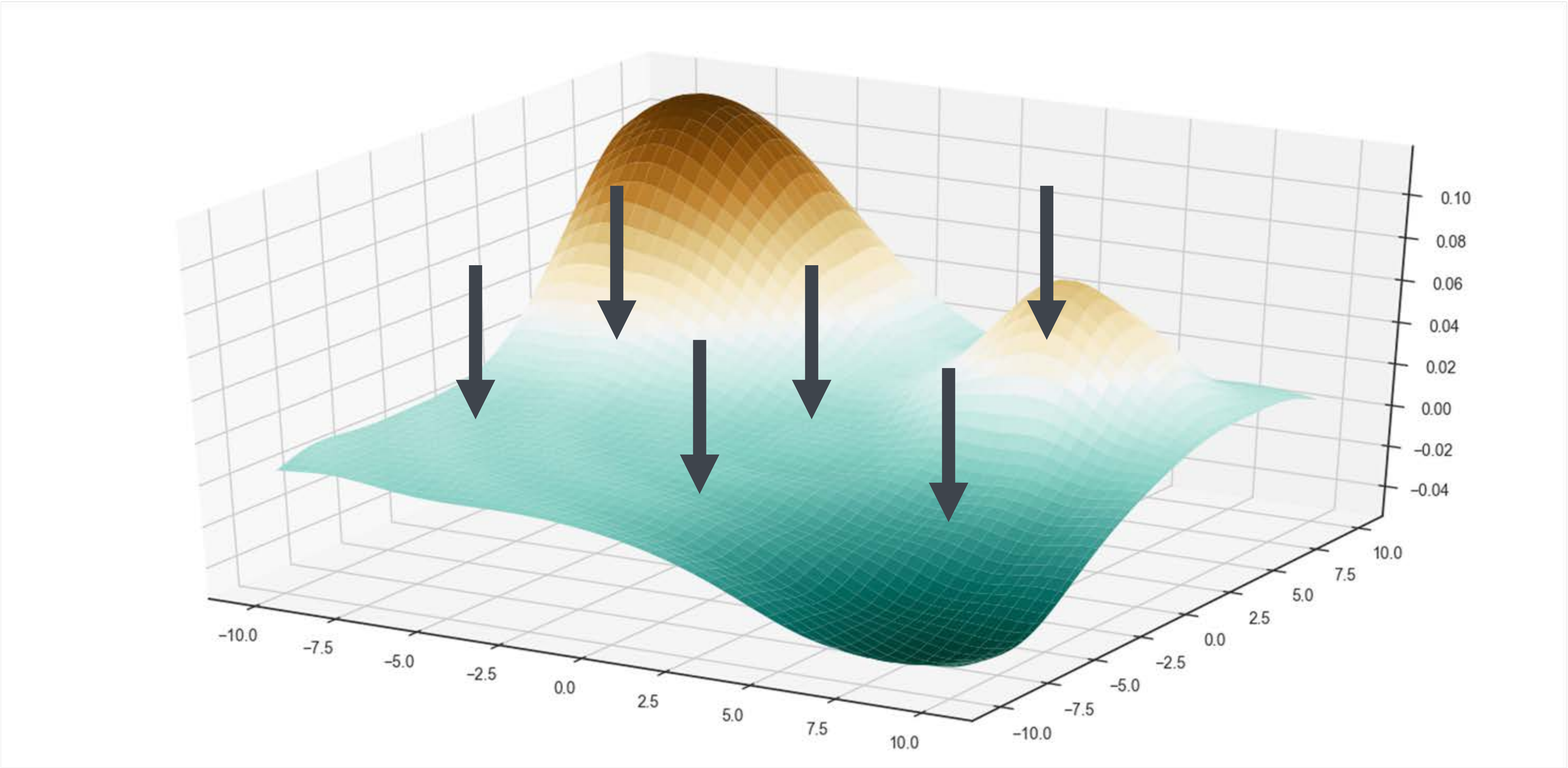
- Random Search:
  1. Generate random design
  2. Keep if better than current best design
  3. Repeat

Optimization Landscape

Here: objective function (y) across two design parameters (x, z)



Random Guessing



Optimizers

- **Heuristic methods** (e.g. Simulated Annealing)
  + Flexible
  - Not guaranteed to find global optimum

- **Exact methods** (e.g. Integer Programming)
  + Guarantees
  - Less flexible objectives

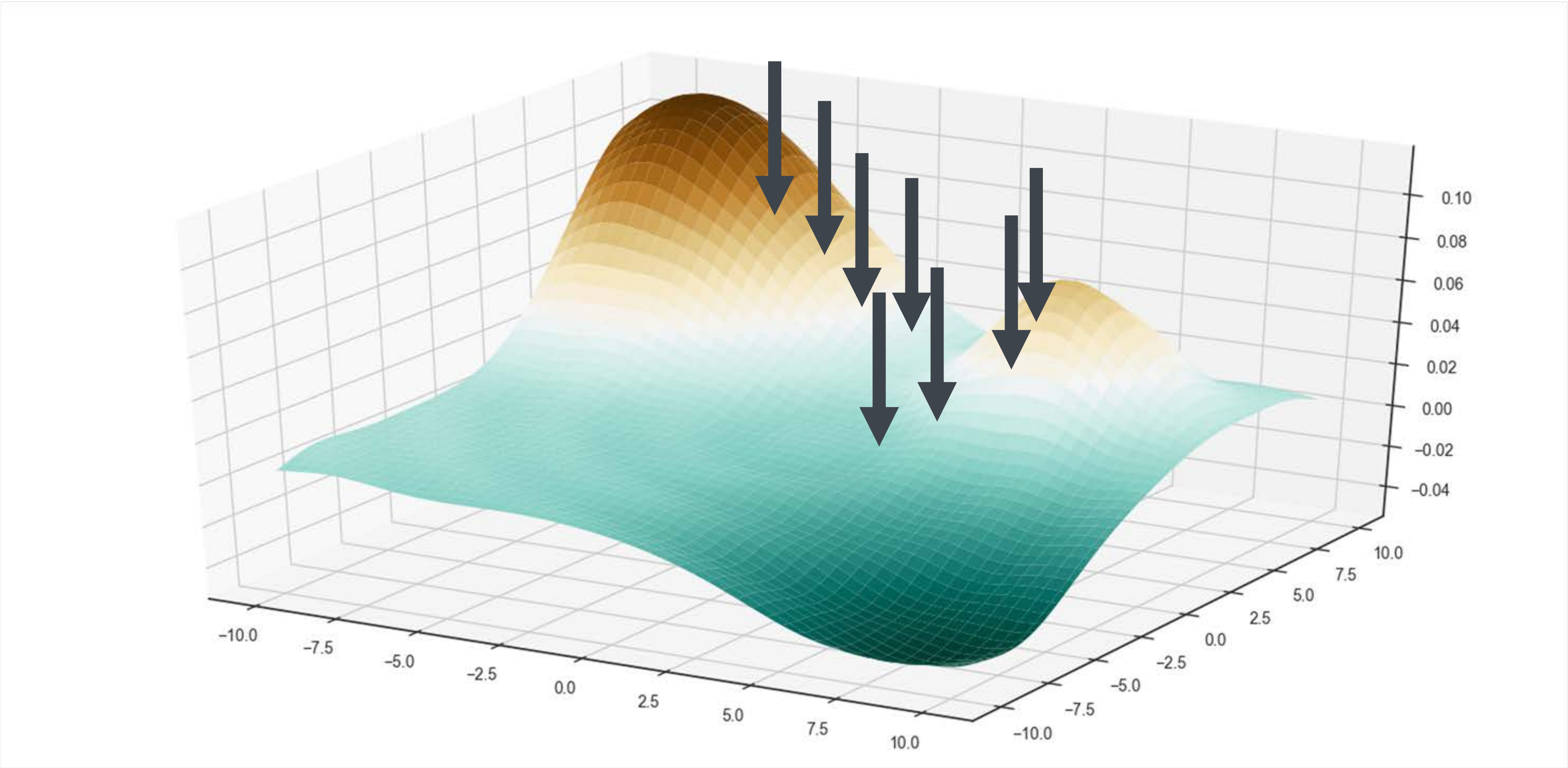
Example: Simulated Annealing

- Metaphor: shaping hot metal
- Flexible at beginning (exploration)
- Gradually more rigid as it "cools down" (exploitation)

Photo by Kateryna Babaieva

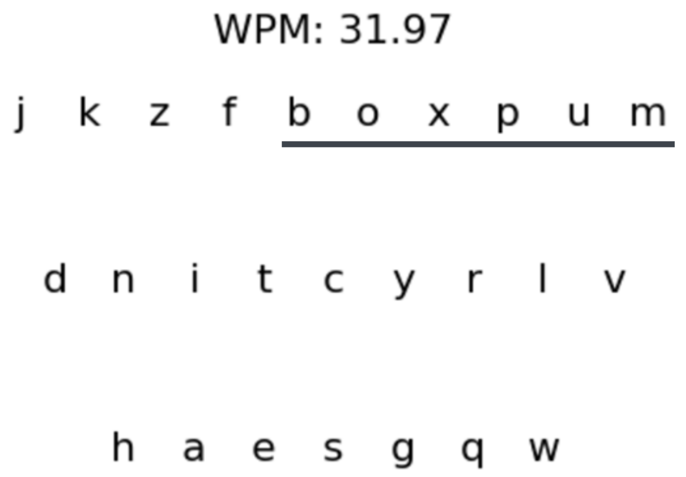
```
For i=0 to N:
  reduce temperature T
  generate neighbor design
  if better: go to neighbor
  else: still go with chance relative to T
```

Simulated Annealing

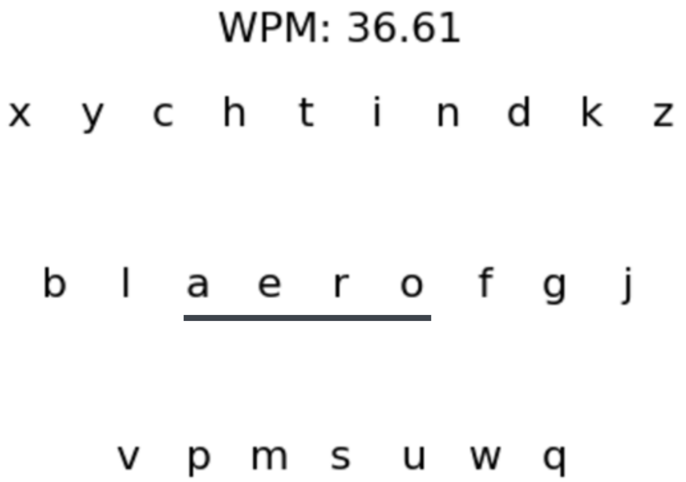


Example Results

“boxpum”
found with random search



“aero”
found with Simulated Annealing



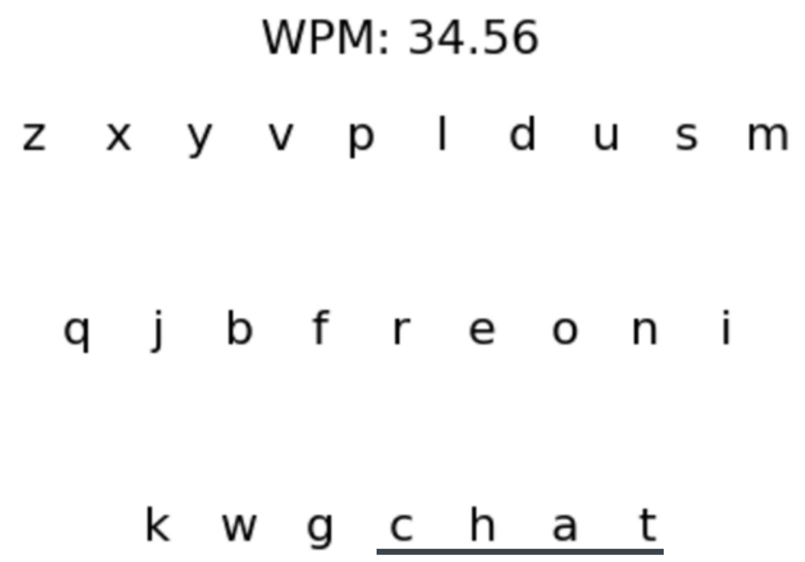
Challenge – can you find a better layout than “aero”?
Use the provided python notebook as a starting point.

Example Results

With a modified objective function

“chat”

found with Simulated Annealing



What was this layout optimized for?

→ Typing with right thumb, reduce thumb stretching

Potential of Optimization-based Design

- Obtaining information on the design problem and a formal specification
- Exploring a large design space comprehensively
- Improving quality and robustness of designs
- Estimating possible improvements
- Supporting human designers
- Optimization during use, personalised UIs

- Requires: Models of user behaviour, formal problem definition / objective function, computational capacity, …

Adaptive and Predictive Keyboards

Motivation: Fast typing without errors

Here: mobile devices

- „Inviscid entry rate“: Bottleneck is not the text entry UI but coming up with the text
- Estimated as 67 WPM

→ Try to reach this on your phone without errors, e.g. in an online typing speed test.

Text entry method	Highest reported entry rate (wpm)
Estimate of the inviscid entry rate	*67*
Physical thumb keyboards	60 [3]
Gesture keyboards	45 [9]
Optimized on-screen keyboards	45 [12]
QWERTY on-screen keyboards	40 [12]
KALQ thumb keyboard	37 [14]
Half-QWERTY	35 [13]
Twiddler	35 [11]
WalkType	31 [5]
ContextType	28 [6]
Disambiguating keypads	26 [7]
Unconstrained handwriting recognition	25 [8]
Dasher	20 [21]
Mobile speech	18 [18]
Quikwriting	16 [15]
Unistrokes	16 [1]
TiltText	14 [22]
Multi-tap	12 [23]
Graffiti	11[1]
EdgeWrite	7 [24]

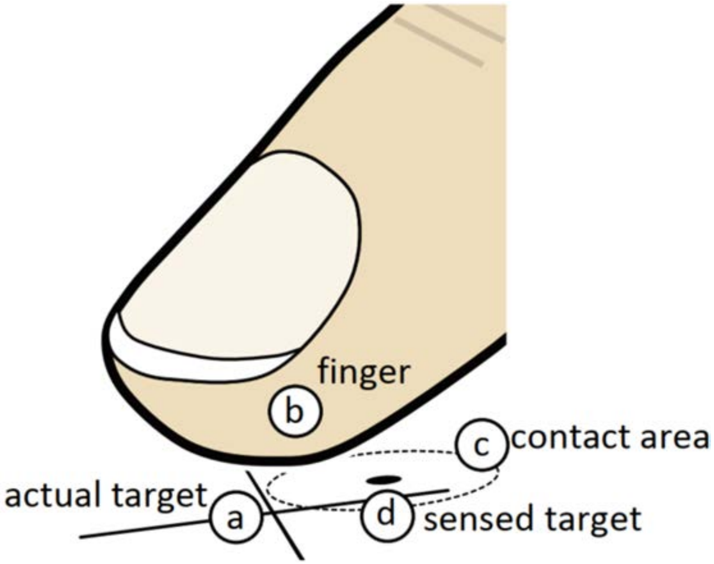
[Kristensson and Vertanen 2014]

Challenges for Mobile Typing

Why is it inaccurate?

Parallax

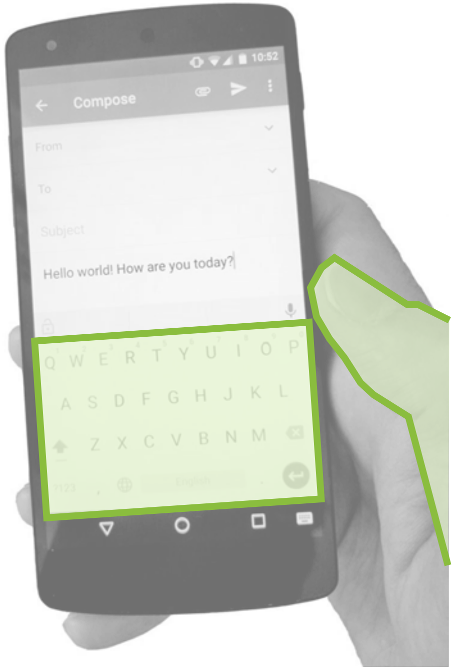
eye – finger - screen



[Holz and Baudisch 2011]

Mobile use

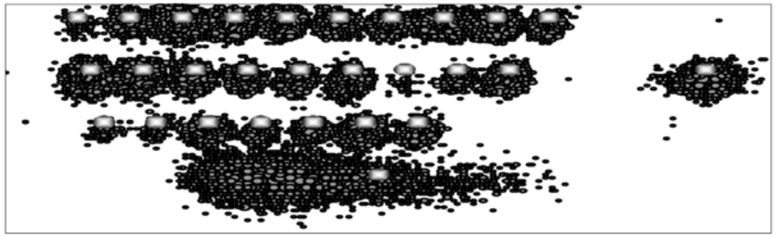
1-2 fingers, small keys, body movement



Variance in Touchscreen Keypresses

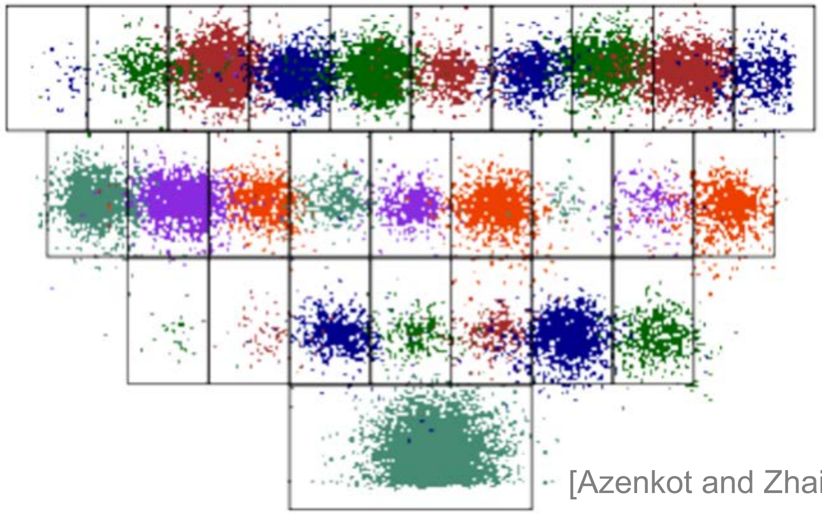
Spread of x,y touch locations around key centres

PDA



[Goodman et al. 2002]

Smartphone

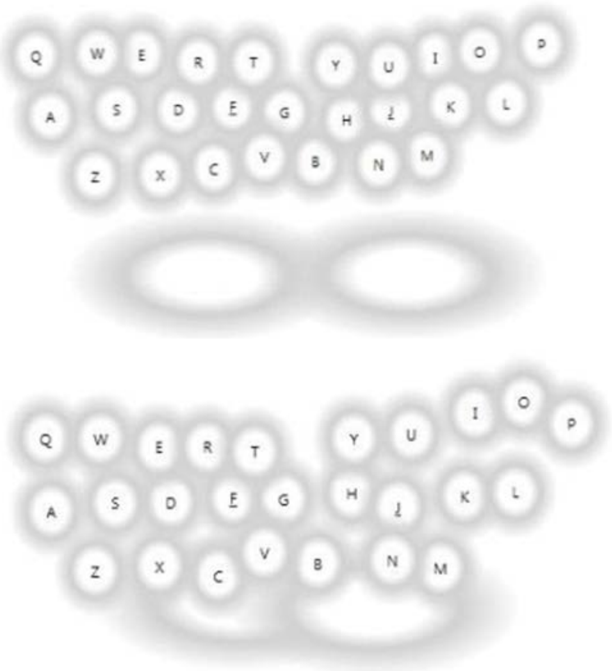


[Azenkot and Zhai 2012]

https://www.microsoft.com/en-us/swiftkey

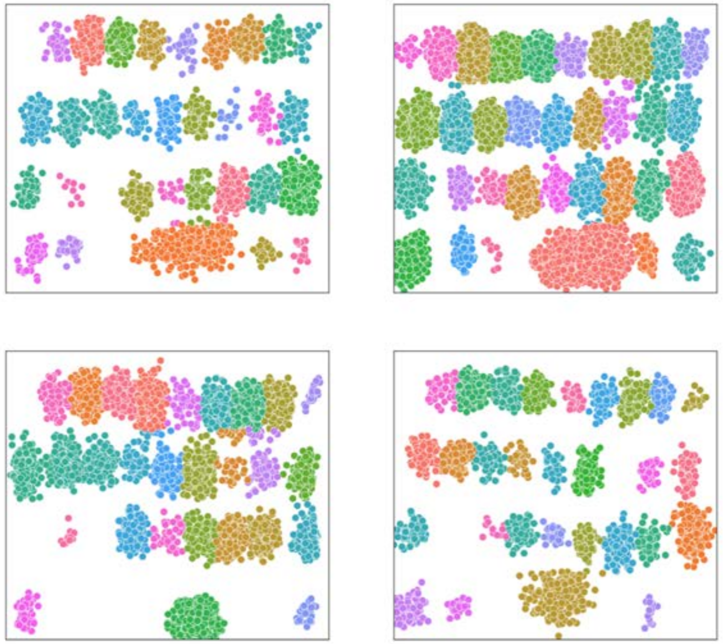
Individual Typing Behaviour

Tabletop



[Findlater and Wobbrock 2012]

Smartphone

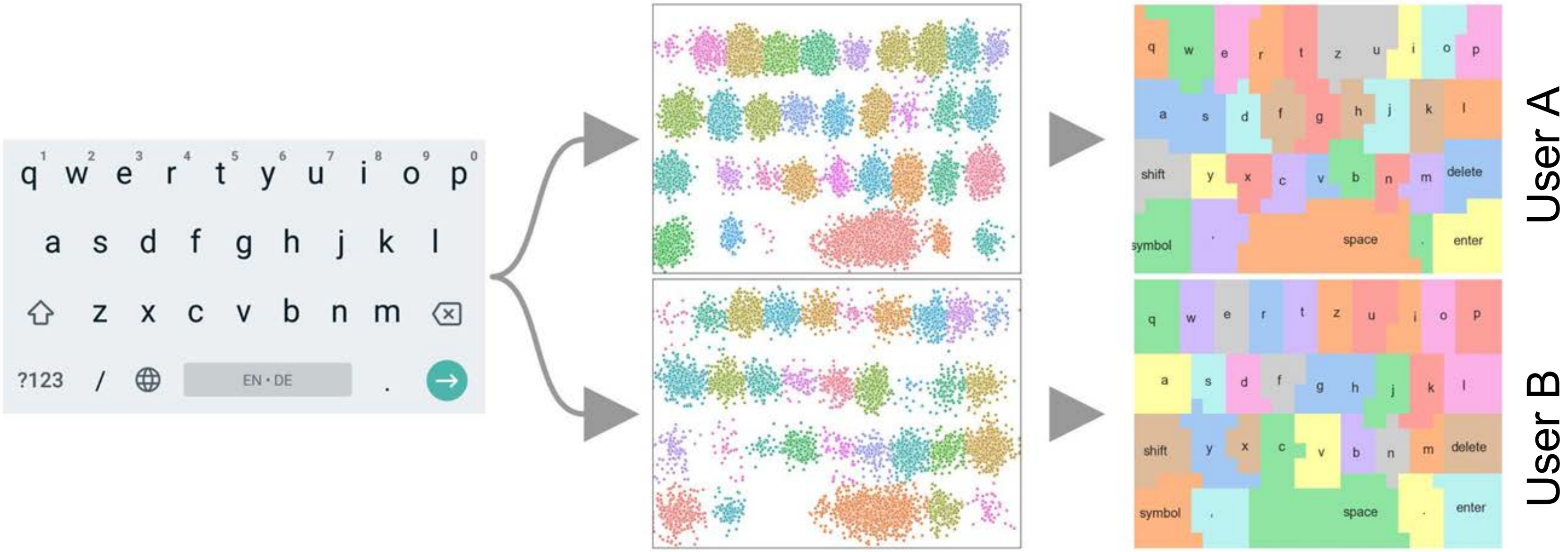


[Buschek et al. 2018]

Adapting Keyboards to Typists

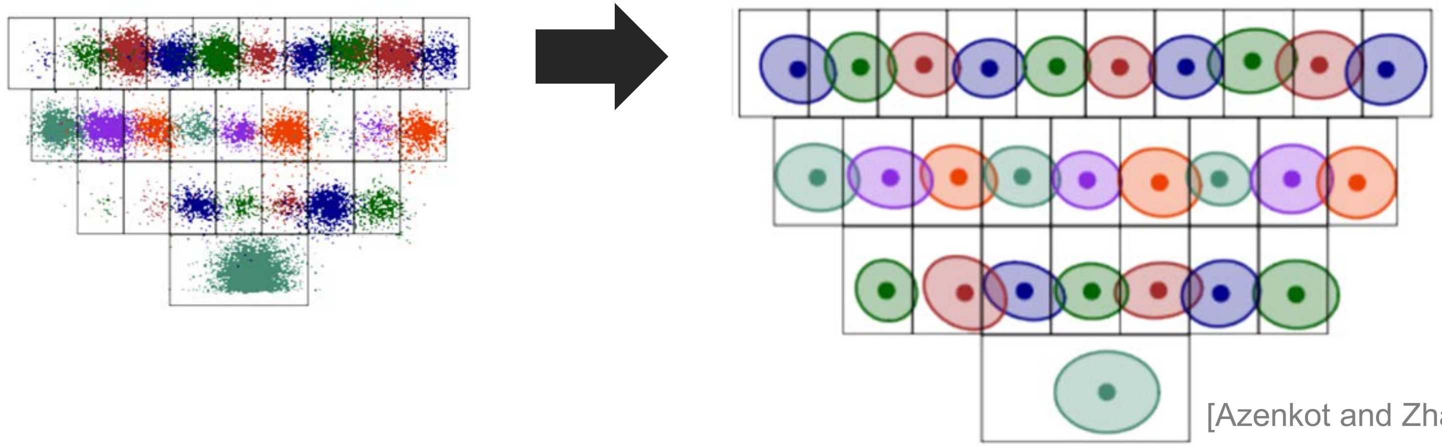
Overview

Visible keyboard **Collect touches** **Adapt underlying key regions**



Modelling Touchscreen Keypresses

From x,y touch points to one Gaussian per key

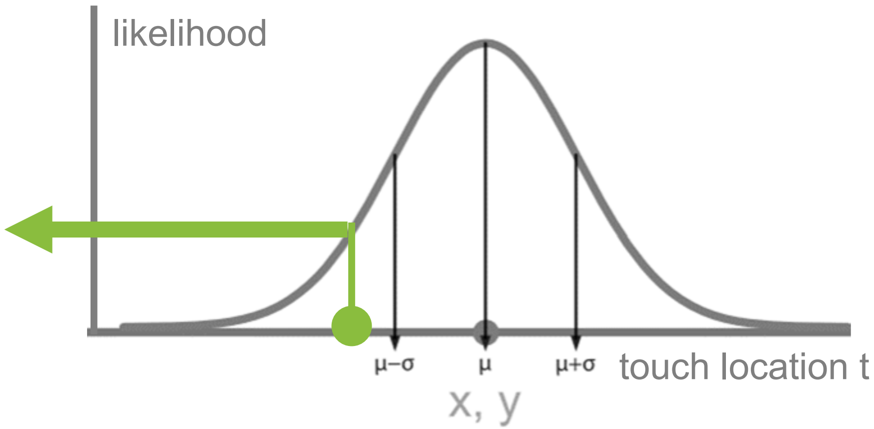


[Azenkot and Zhai 2012]

Gaussian key model:

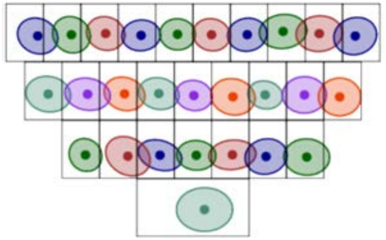
(shown in 1D here)

$$p(t|k) = \mathcal{N}(\mu_k, \sigma_k^2)$$



Probabilistic Keyboard Model

Which key does the user intend to press? i.e. „input decoding“



Gaussian key model

Language model

e.g. based on last five characters: $p(k_n|k_{n-1}..k_{n-5})$

$$k' = \underset{k \in K}{\operatorname{argmax}} \left(\underbrace{\frac{p(t|k)p(k)}{p(t)}}_{\text{Bayes' rule } = p(k|t)} \right) = \underset{k \in K}{\operatorname{argmax}} \left(p(t|k)p(k) \right)$$

predicted keypress

Bayes‘ rule

$= p(k|t)$

Evaluate and colour ***k‘*** for each pixel

DIY: Probabilistic Keyboard Model

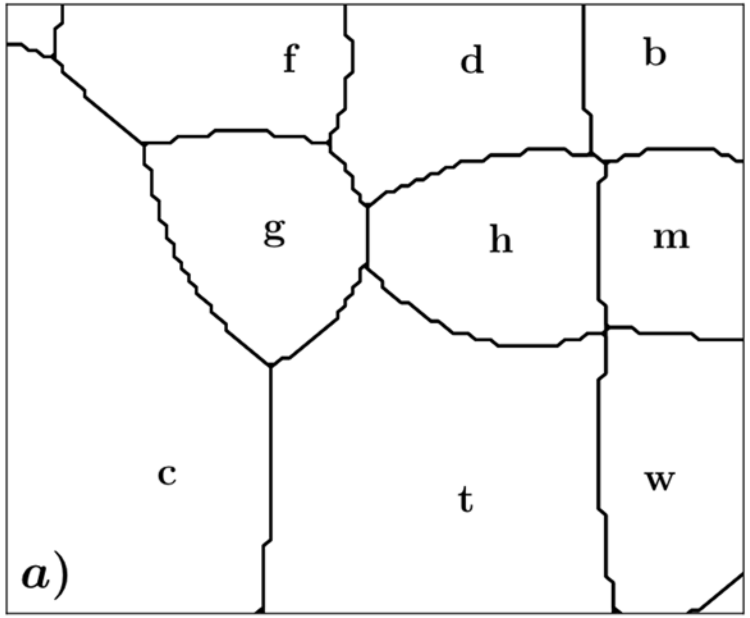
```
touchX = ... // touch X coordinate
touchY = ... // touch Y coordinate
num_keys = ... // number of keys on keyboard
means = [...] // list of all key means (2D key locations)
variances = [...] // list of key variances (real values) or covariances (2x2 matrices)

probs = [] // list to store the likelihoods of each key being pressed
sum = 0 // variable to store sum of likelihoods for normalisation (see below)

for k = 0 to num_keys: // iterate over all keys
    // evaluate touch location under distribution of the key*:
    prob_t_given_k = multinormal_pdf(touchX, touchY, means[k], variances[k])
    // likelihood of key without touch info; uniform (here), or based on language*:
    prob_k = 1/num_keys
    // store product and add it to the sum of all likelihoods*:
    probs[k] = prob_t_given_k * prob_k
    sum = sum + probs[k]

// normalise, so that the likelihoods add up to 1*:
probs = probs / sum //note: "/" is element-wise division

// find most likely key:
pressed_key_index = argmax(probs)
// TODO for adaptation: update means and variances with new touchX and touchY
```

* in real implementation use logarithm and corresponding operations for numerical stability

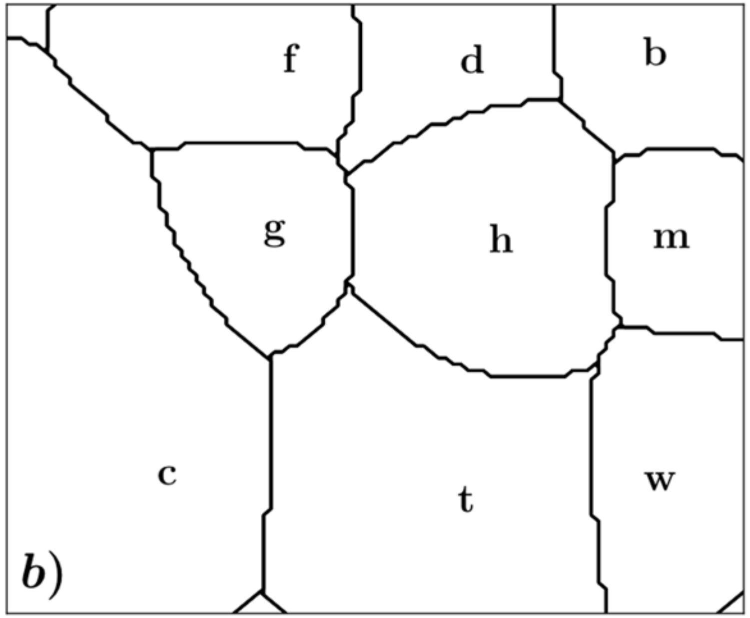
Language Model Influence

Example: bigram model for English

After „**n**“:

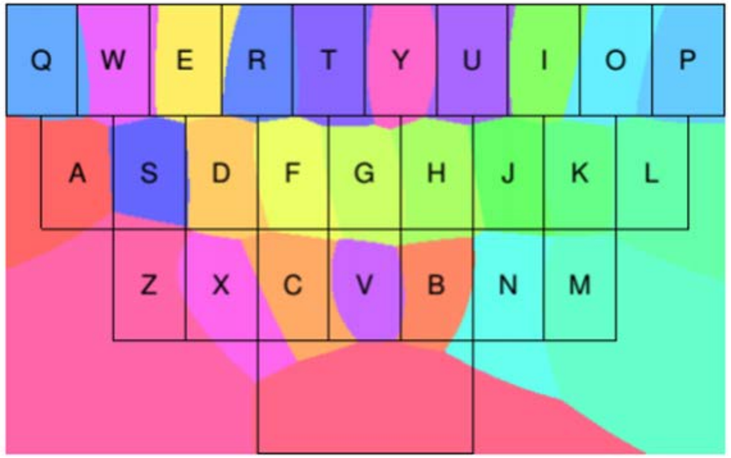


After „**t**“:



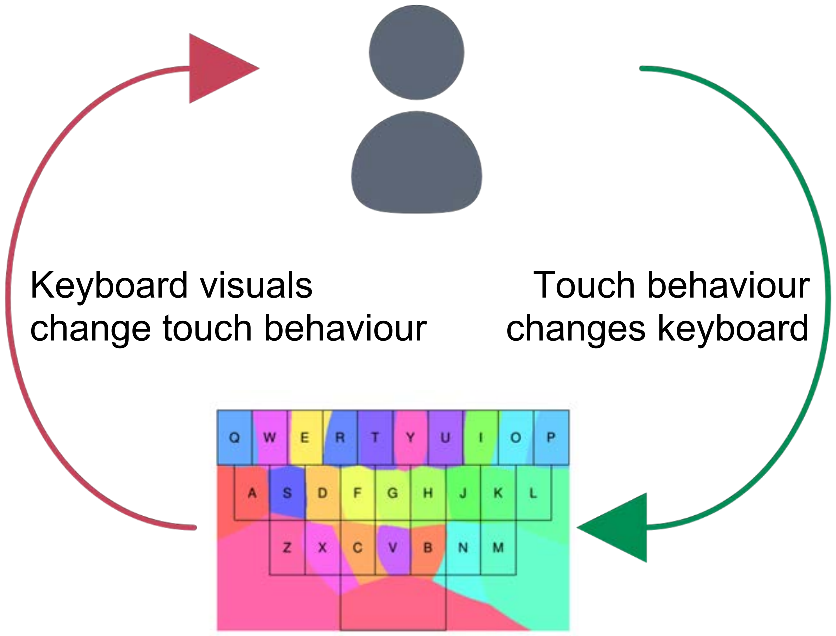
Adaptation in the Background

Why do our keyboards not look like this?



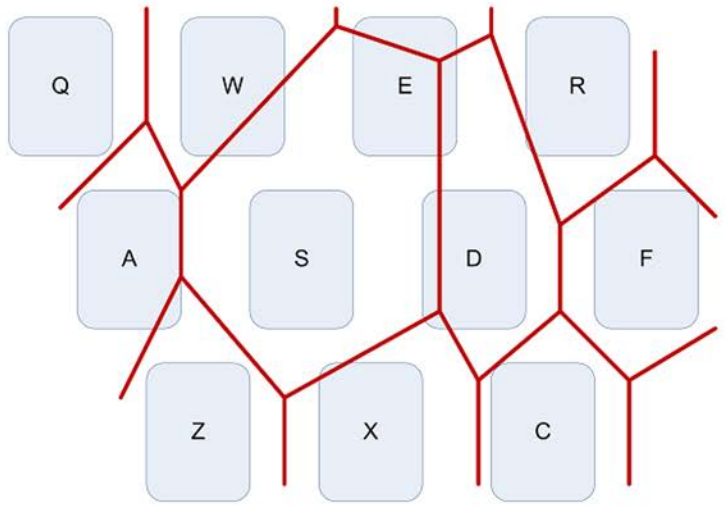
[Yin et al. 2013]

→ Avoid co-adaptation of user and system



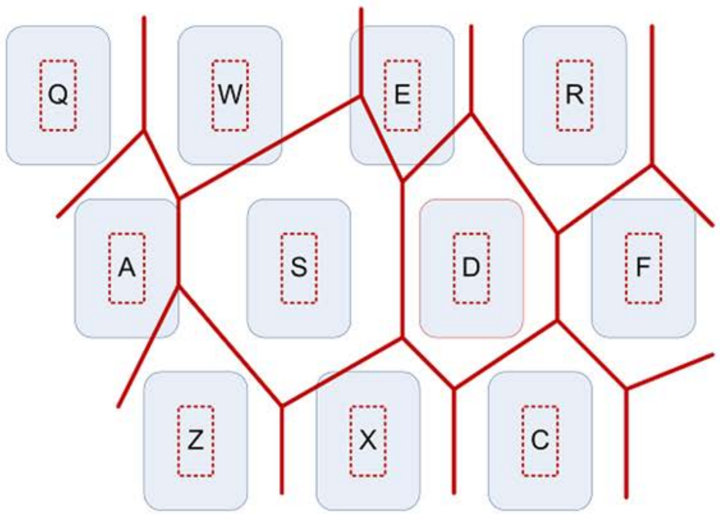
Adaptation vs Distortion

Unlimited adaptation



Here: (almost) impossible to type „e"!

With protected key region



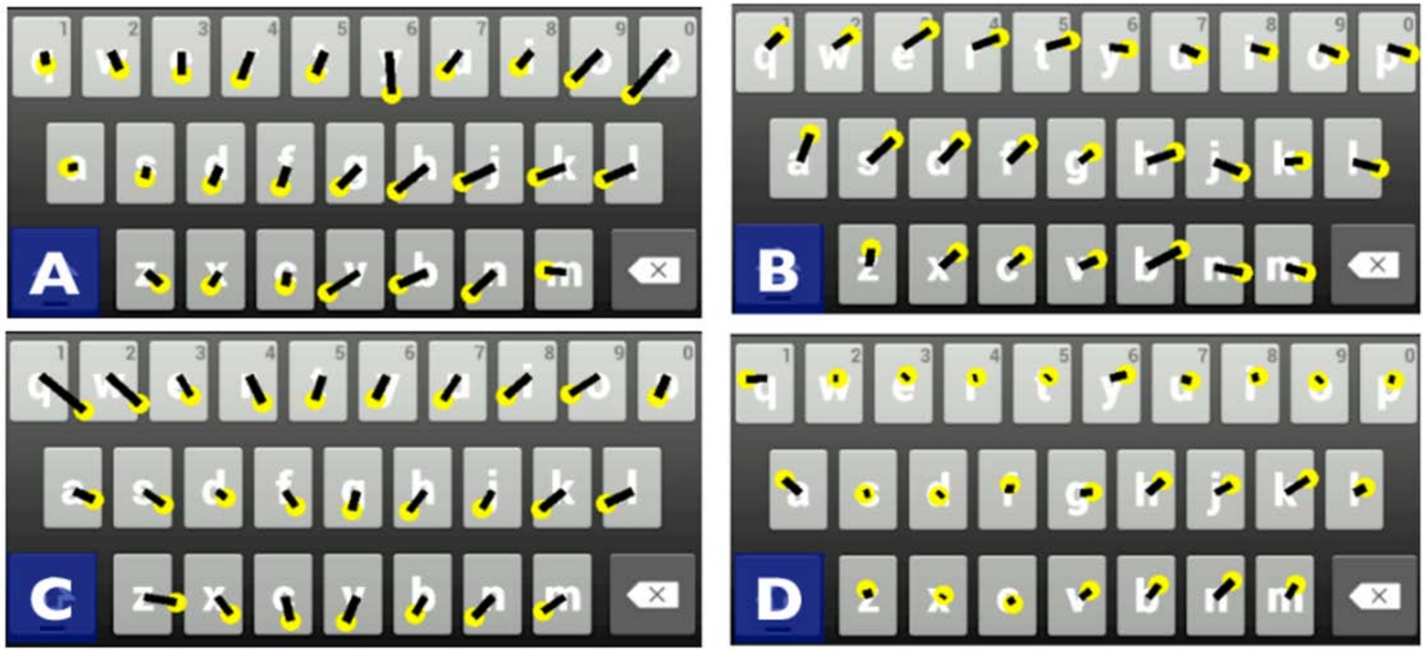
[Gunawardana et al. 2010]

Context Adaptations

e.g. hand posture – „ContextType“, Goel et al. 2013

Left thumb

Right thumb



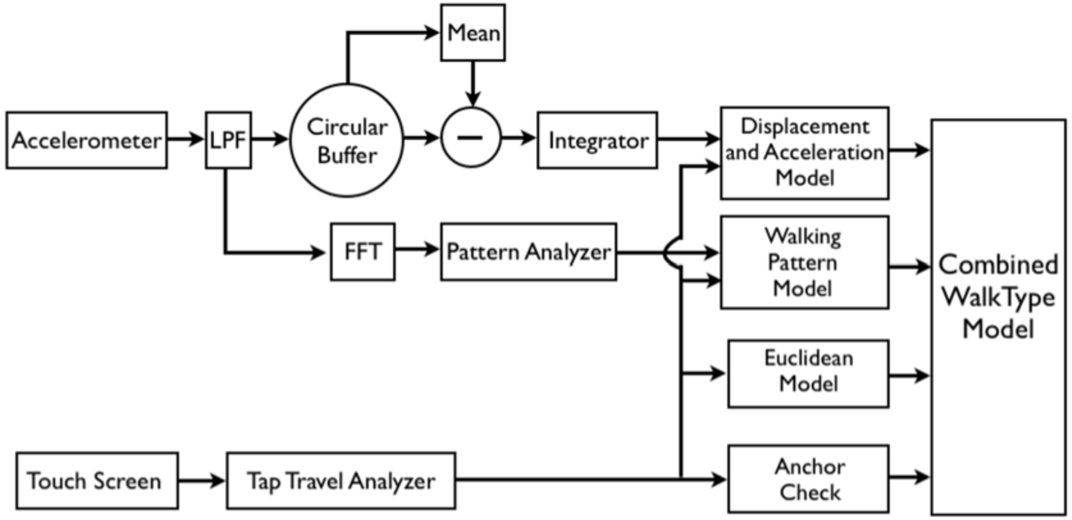
Index finger

Two thumbs

[Goel et al. 2013]

Context Adaptations

e.g. walking – „WalkType“, Goel et al. 2012



[Goel et al. 2012]

Notebook Example

Visualising adaptive keyboards

Decoding Typing Sequences

- Infer intended input after entering whole word or sentence
  - \+ More evidence for inference
  - \+ No need for user to pay attention to intermediate output
  - \- No intermediate feedback

- Example (sentence-based decoding):

„pleaseforwarxmetheatachement“

Hit enter

„Please forward me the attachement.“

[Vertanen et al. 2015]

Sequence Decoding, formally

- Sequence of user‘s intended keys/letters (i.e. unknown to system)

$$s = \{k_1, k_2, ..., k_n\}$$

- Sequence of user‘s touches (i.e. system‘s observations)

$$o = \{t_1, t_2, ..., t_m\}$$

- Can we infer *s* from *o* ?

$$s' = \underset{s}{\operatorname{argmax}} \left(p(o|s)p(s) \right)$$

Note: Same approach as for a single touch but now we have sequences of touches and keys

$$k' = \underset{k \in K}{\operatorname{argmax}} \left(\frac{p(t|k)p(k)}{p(t)} \right) = \underset{k \in K}{\operatorname{argmax}} \left(p(t|k)p(k) \right)$$

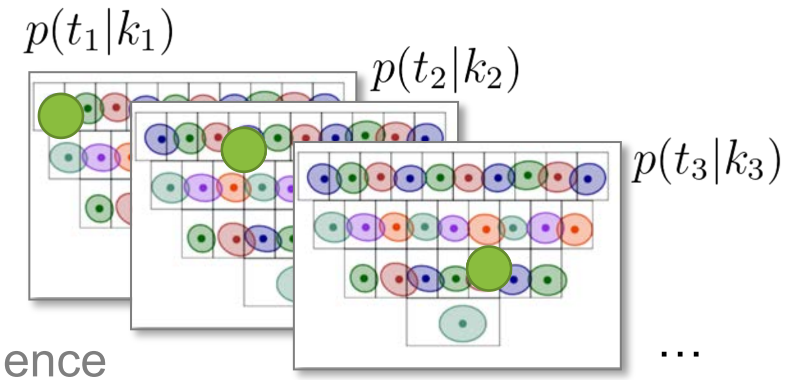
Probabilistic Model for Sequences

See notebook for an example implementation

Prior over letter sequences,
i.e. probability of *s* in a language,
i.e. a language model

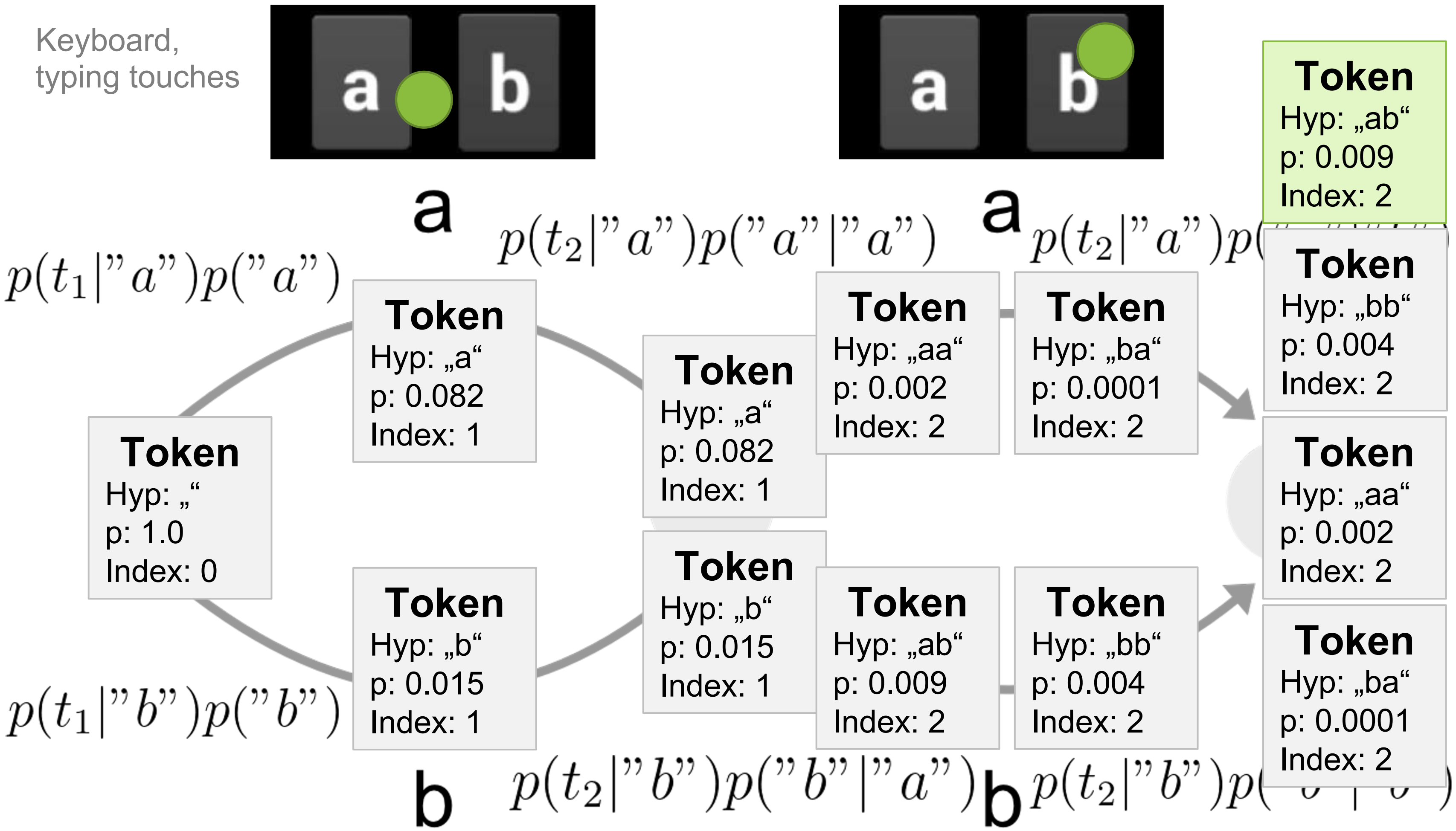
$$s' = \underset{s}{\operatorname{argmax}} \left(p(o|s)p(s) \right)$$

$$p(o|s) = \prod_{i=1}^{m} p(t_i|k_i)$$



Gaussian key model, now for a touch sequence
(i.e. likelihood of observing the touch sequence *o* under the assumption that the user intended to write *s*)

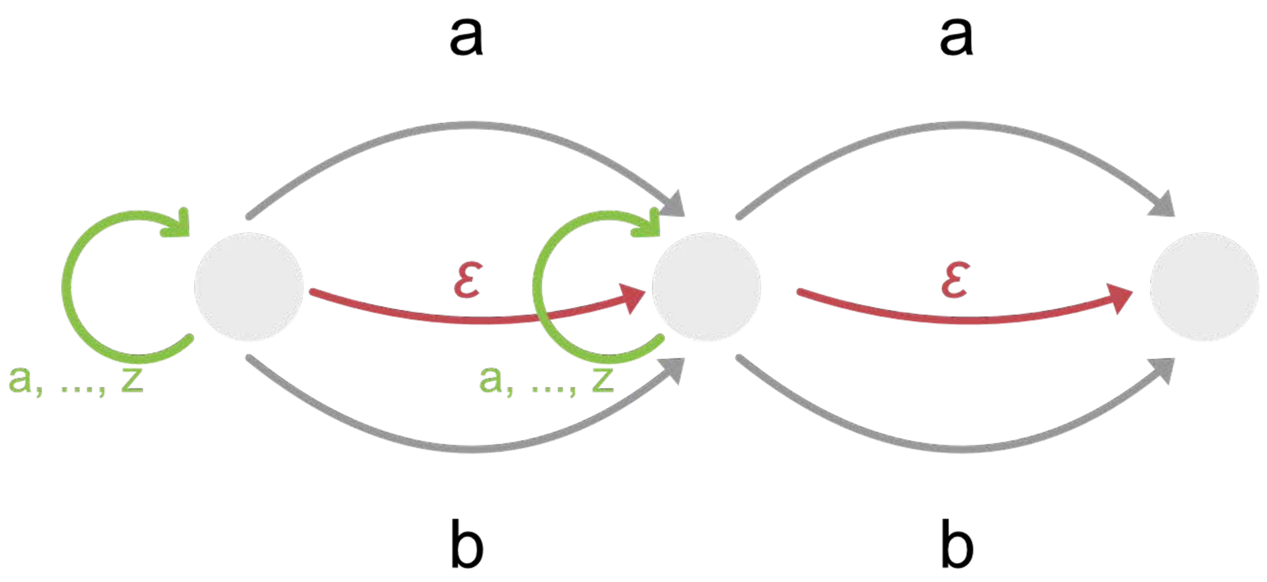
Decoding Typing Sequences
Token passing algorithm



Decoding Typing Sequences

With insertion and deletion

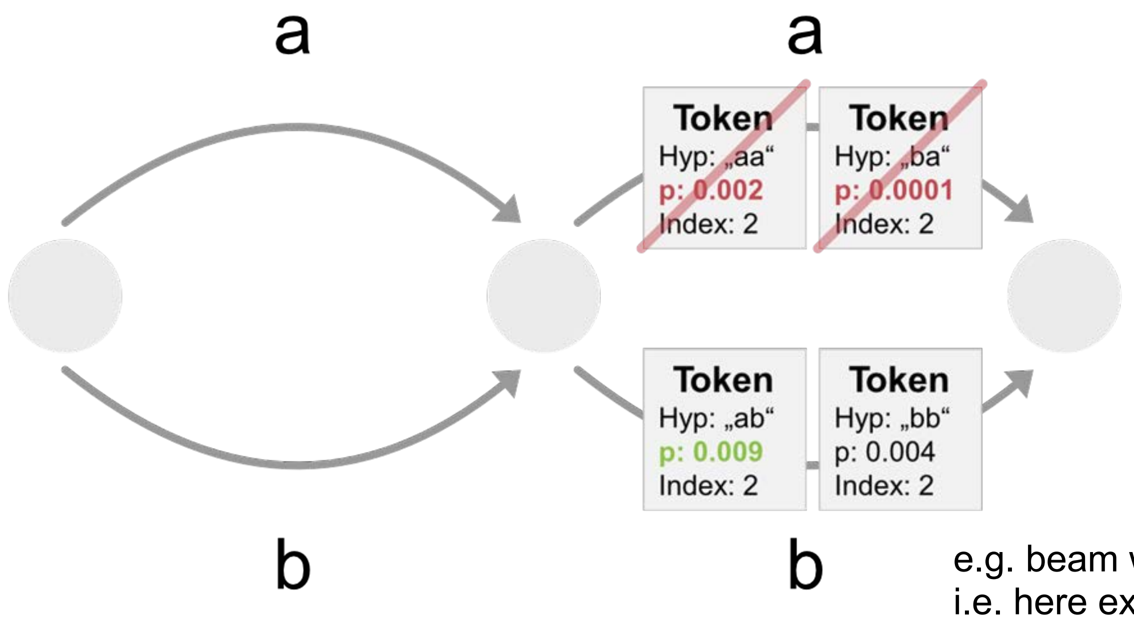
- Previous slide: Substitution-only decoder
- Extensions: **insertion** and **deletion** transitions, with „penalty“



Decoding Typing Sequences

With beam search / pruning

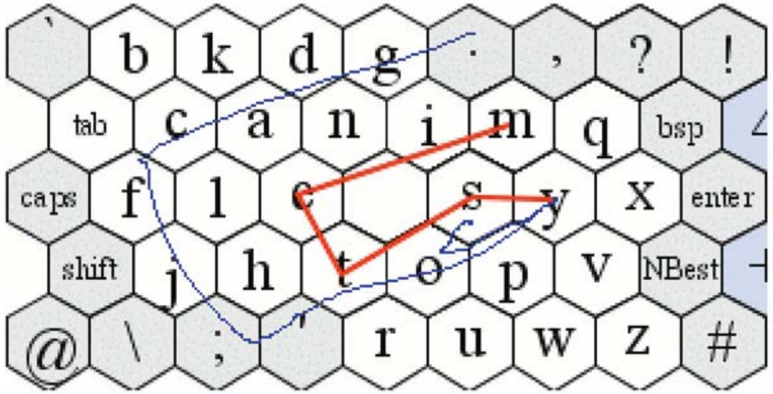
- Problem: Large search space
  Substitution-only → exponential, Insertion → infinite
- Solution: **Beam search / pruning**
  Per index, only propagate tokens that are within a certain range (=„beam width") of the probability of the most likely token.



e.g. beam width = 0.005,
i.e. here exclude p < 0.009-0.005=0.004

Gesture-based Decoding

Infer intended word from shape of finger trace on the keyboard



„SHARK²“ [Kristensson and Zhai 2004]

Microsoft SwiftKey (screenshot Nov 2020)

Gesture-based Decoding

Shape model

Language model

$$w' = \text{argmax}_{w \in W}(p(trace|w)p(w))$$

Stored template (ideal) shapes for all words in dictionary W

…

Distance metric

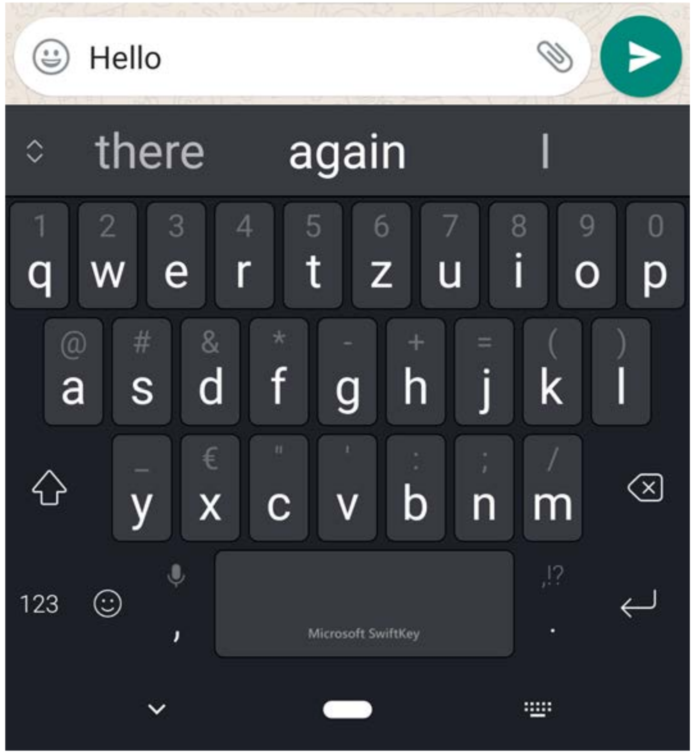
e.g. see Kristensson and Zhai, 2004

User‘s touch trace

Word Prediction

- So far: Inference used touch input
- Now: Predict *next* word that user has not yet started to type, only using language context

$$p(w_t | w_{t-n} \dots w_{t-1})$$



- E.g. n-gram word models, i.e. context of last n-1 words
- More recently: Deep Learning to include larger context

Summary

- Improving keyboards by probabilistically combining input information with language information

- **Adaptation:**
  - Individual input behaviour → adaptation to typist
  - Further sensors → adaptation to context

- **Prediction/Decoding:**
  - Single touch + language context → current key
  - Touch sequences + language context → current word/sentence
  - Language only → next word(s)

Notebook Example 2

Sequence decoding

References (Part 1)

- Kristensson, P. O., & Vertanen, K. (2014). The inviscid text entry rate and its application as a grand goal for mobile text entry. *Proceedings of the 16th international conference on Human-computer interaction with mobile devices & services*, 335–338. https://doi.org/10.1145/2628363.2628405
- Kristensson, P.-O., & Zhai, S. (2004). SHARK2: A large vocabulary shorthand writing system for pen-based computers. *Proceedings of the 17th Annual ACM Symposium on User Interface Software and Technology - UIST '04*, 43. https://doi.org/10.1145/1029632.1029640
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- Yin, Y., Ouyang, T. Y., Partridge, K., & Zhai, S. (2013). Making touchscreen keyboards adaptive to keys, hand postures, and individuals: A hierarchical spatial backoff model approach. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 2775–2784. https://doi.org/10.1145/2470654.2481384

Further Reading:

- Bi, X., Li, Y., & Zhai, S. (2013). FFitts law: Modeling finger touch with fitts' law. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 1363–1372. https://doi.org/10.1145/2470654.2466180
- Oulasvirta, A., Kristensson, P. O., Bi, X., & Howes, A. (Hrsg.). (2018). *Computational Interaction*. Oxford University Press.

References (Part 2)

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