

# 1 Introduction

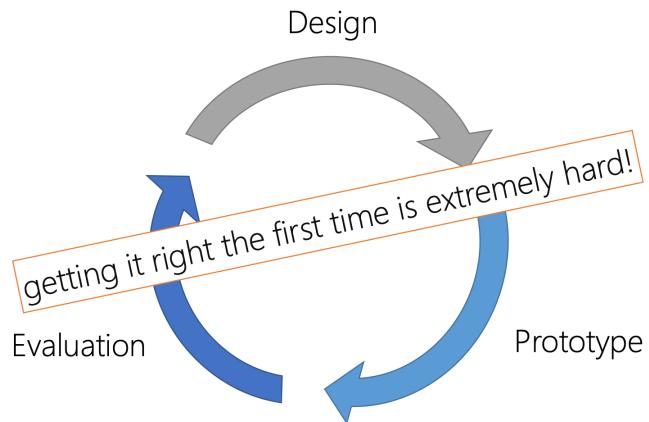
**Goal of course:** Understand principles of user-centered design and able to apply these to practice. Learn about the basic notions of Computational Design in HCI context.

**Moore's Law** Computational power grow exponentially. Transistor count doubles every two years. Also with RAM and pixel densities. However: Human capabilities stay stable.

**Good System design** Accounts for human capabilities, human error and exceptional circumstances.

**Human Computer Interaction** Concerned with design, evaluation and implementation of interactive computing systems for human use.

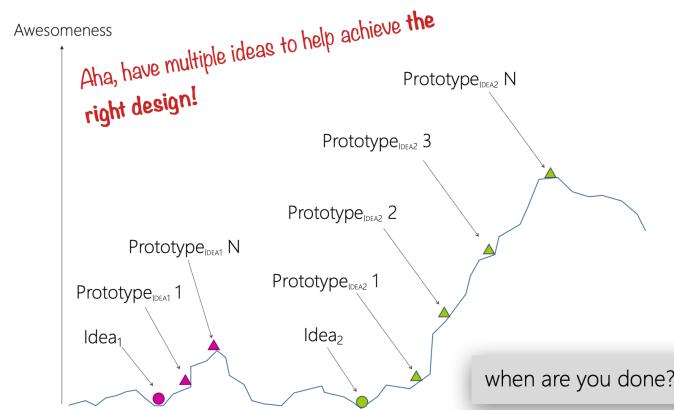
## Process in HCI



Formative : understand problem and user to inform our design. Evaluative: understand how well design works. Also detects mistakes in design.

# 2 User-centered Design

**Design intention vs User Needs**  
**Prototyping as an iterative process**



Does the design work properly in the context of use? If not fix the problems and carry out more tests.

**Early focus on users and tasks:** Cognitive, behavioral, anthropomorphic AND attitudinal characteristics.

**Empirical Measurement:** Observe user's reactions and performance in scenarios, manuals simulations and prototypes, record and analyze.

**Root-Cause Analysis** Problems need to be discovered (find the right problem to solve, not any problem to solve) and find the right solution to it.

### Need finding

Users rarely know what they want. Cannot imagine what is possible. Instead look at tasks, context:

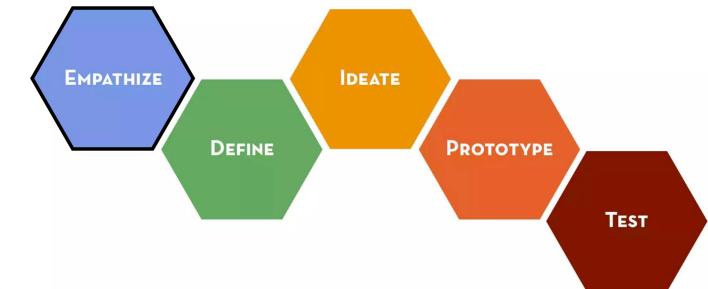
- What information needed?
- Identify collaborators
- Why is task achieved the way it is?
- Identify tasks in existing behavior
- Identify tasks in future scenarios

We ourselves are not representative of the typical user. To learn about customers conduct interviews, self-reports and logging/analytics. Also observe users performing tasks and understand their cognition.

**Understanding the User** Active observation is not knowing yet what you are looking for.

- Immerse
- Observer
- Engage

## Design Thinking Process



### Goals of Need finding

- Distill useful and actionable insights
- Make meaning from needfinding data
- reframe problem to guide solution search

We start with closed ended questions and move to open ended questions: "What's and why's of feelings". Engage people in their environment. The goal is to find inspiring users, that surprise us and bring us to game-changing ideas.

### Needs vs. features vs. requirements

Requirements are goals that the system needs to accomplish. Solutions fulfill requirements. What does the user want to accomplish and how is he doing it? What would they like to be doing? What are they currently disliking? For what is the system usable and what tasks will it support? Answering these questions will make the system more usable.

There are tons of methods to needfinding such as:

- Task Analysis
- Interviews
- Affinity Diagrams
- Cognitive Walkthrough
- Questionnaires
- Focus Groups
- Diary Studies
- "Speed dating"
- etc.

### Interview

Interviewee speaks 90 percent of time and stays on topic. We choose participants to be representative target users, either current or potential future users. We like both experts and typical users. Try to provide and explanation into how users make sense to themselves.

**Common pitfalls in interviews** Suggesting answers.  
Hypothetical questions.

**Diary Study** Ask people to record events as they happen.  
User diary studies for rare events, easily forgotten events and events where the actual frequency is important.

Problems with diary studies is that the simple tracking of their behaviors will change their behaviors.

**Retrospective Survey** Ask about things happened in the past. Use this for critical events (well remembered), recent and memorable events, rare events that had a big impact and are memorable. DO not use them for hard to remember events.

**Artifact Analysis** Look at things people leave around to understand a problem they might have. Use this for physical spaces (physical artifacts from workflows), tasks involving artifacts and interactions generating artifacts (emails, social media posts etc.). Only use if there are in fact artifacts and there is no faster way to learn information.

**Contextual Inquiry** Ethnographics or participatory design, combining aspects of other methods. Interviewing, observing in the context of work. Goal is to discover real requirements of the work. Interview people while they are working and gather real artifacts. User decides the tasks, but you decide the focus.

## Key Differences

interviews, surveys, focus groups

summary data & abstraction

what customers say

subjective

limited reliability of humans

what users/customers think they want

Contextual Inquiry

in-situ experience & data

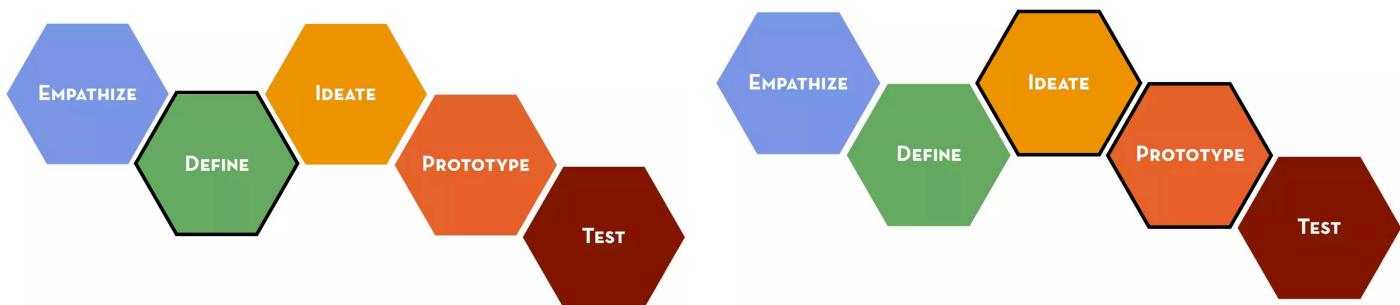
what users do

objective

spontaneous, as it happens

what users actually need

**Result of Need-Finding** We know what works and what does not yet exist. Problems and incomplete parts in process. So we have a long list of problems.



**Define** This part is more a focussing part and not flaring. Figure out what is important from collected data. Group info and find relations.

### Affinity Diagrams

Data with affinity to each other are grouped together to form category. Groups are given labels, can be one or more categories in the end. Identify user, need and insight. Combined to create point of view.

Good point of view insires the team, frames the problem in a focussed way. Empowers to make decisions and fuels brainstorming by suggesting "how might we" statements.

**The elastic user** The elastic user can mean everyone and also noone. Vague and unfocused, lack of specifics makes it easy to rationalize any design.

**Personas** Personas are precisely described. Act as stand-in for real users. Guide design decision. Fictitious but based on knowledge of real users. Informed from observations. Personas are not elastic, don't make them fit the prototype.

**Ideate** Flaring here, not focussing anymore.

### Ideation techniques

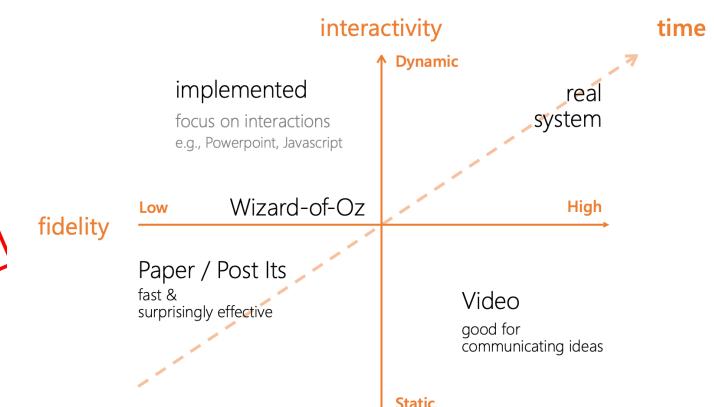
- brainstorming
- mind-mapping
- storyboard
- sketching
- low-fi prototyping

## 3 Prototyping

Prototypes develop from sketches over time and are more defined in their criteria weights. Make multiple prototypes to evaluate different approaches and check for failure/success. Prototypes help us understand requirements and specifications of the idea. They answer a specific question.

*Vertical vs. horizontal* Vertical provides critical path of one or few features (real feature on that path is completed). Horizontal provides only overview with little to no functionality.

### Fidelity and Interactivity



**Paper prototypes** Are rapid and cheap.

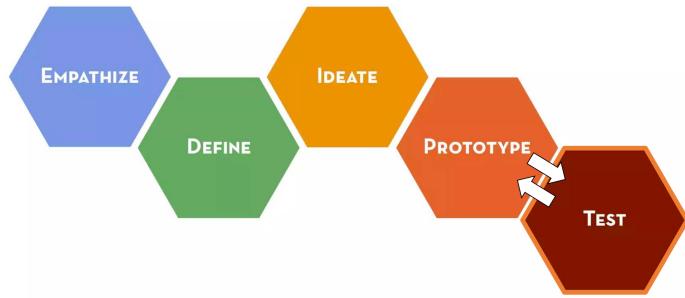
**Wizard of Oz** Interprets user input and simulated a system response. Allows rapid testing of complex features before implementing.

### MidFi-Prototypes

Physical (paper, cardboard, lego etc.) to software.

- Powerpoint, Keynote

- AdobeXD, Figma



### Analytical vs. Empirical

#### *Analytical*

Look at inherent attributes of the design, rather than the design in use. Intrinsic characteristics of the design. Examples are usability/UX inspection methods, design walkthroughs, heuristic evaluations.

#### *Empirical*

Based on how well a design or design change pays off in terms of real observable usage. Includes quantitative and qualitative data. Examples are usability/UX scores, controlled experiments and case studies.

### Formative vs. Summative

#### *Formative*

Helps form the design. Part of iterative process. Evaluations done during testing. Mainly collects qualitative data but also quantitative. Focuses on what is not working.

#### *Summative*

Helps sum up the design. Evaluates the success of the finished product, and compares with competitors. Collects quantitative data, and focuses mainly on what is working.

### Evaluation criteria for UI design

### *Usability*

Extent to which product can be used by specific users to achieve goals with effectiveness, efficiency and satisfaction. Five quality components of Usability:

- learnability
- efficiency
- memorability
- errors
- satisfaction

### *User Experience*

Totality of the effect(s) felt by a user as a result of interaction with the usage context of a system, device or product.

It includes:

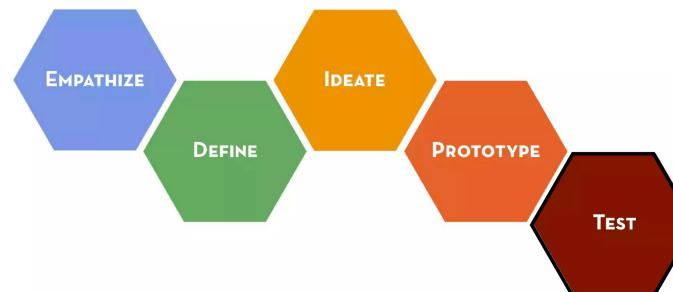
- Usability
- usefulness
- emotional impact
- savoring memory after interaction

It embraces seeing, touching, thinking about system or product and admiring it and its presentation. Focuses on holistic experience of user.

**Affordances** Actions that the design of an object suggest to the user. Provide strong clues to how objects are to be used without labels, explanations or manuals.

Works for both physical objects and software. Up to a certain degree of complexity.

## 4 Analytical Investigation



Is performed by usability experts and domain experts. They use their knowledge of users and technology to assess the usability and user experience. Result can be formal or informal reports.

Two types of analytical investigation:

1. Usability and UX inspection (Design, cognitive walkthroughs, heuristic evaluation)

2. Predictive user performance models (GOMS, KLM)

### 1. Usability and UX inspection

#### *Cognitive Walkthroughs*

Evaluate design by experts, with the goal of exploring the design on behalf of the users. Difference to UX inspection: UX inspection only one aspect of a design presented to experts. Cognitive walkthrough: More focused on ease-of-learning.

#### *Heuristic Evaluation*

Heuristics are design guidelines. Examine the interface, judge its compliance with recognized usability principles (heuristics). Is cheap, fast and easy to use. Is developed for inexperienced practitioners, experts can be limited through heuristics. Can be done on paper-only prototypes.

1. Briefing to tell evaluators what to do
2. Each evaluator inspects interface alone (at least twice, get feel for flow of interaction and scope of system, also focus on specific interface elements)
3. evaluators aggregate findings
4. debriefing session, discussion of possible redesigns for major UX problems, look at positive aspects

Optimally between 3 and 5 evaluators. Limited because it does not encourage to take a rich and comprehensive view of interaction. It's only a rough outline, and experts find problems with inspection not heuristics. Danger of overestimating heuristics and use for any evaluation.

#### *Nielsen's Heuristics*

1. *Visibility of system status*

System should always keep users informed about what is going on, through appropriate feedback in reasonable time.

2. *Match between system and the real world*

System should speak the users' language, with words, phrases and concepts familiar to the user, rather than system-oriented terms. Follow real world conventions, make info appear in natural and logical order.

3. *User control and freedom*

Users need a clearly marked emergency exit from unwanted state, if chosen system functions by mistake.

#### 4. Consistency and standards

User should not have to wonder whether different words, situations or actions mean the same thing.

#### 5. Error prevention

Good error messages, but better is design that prevents a problem from occurring in the first place. Eliminate error-prone conditions or check for them and give users a confirmation option before committing to the action.

#### 6. Recognition rather than recall

Minimize the user's memory load by making objects, options and actions visible. Instructions for use of the system should be visible or easily retrievable, whenever appropriate.

#### 7. Flexibility and efficiency of use

Accelerators may often speed up the interaction for the expert user, such that the system can support both inexperienced and experienced users.

#### 8. Aesthetic and minimalist design

Dialogs should not contain irrelevant or rarely needed information. Extra infos compete with the relevant units of information.

#### 9. Help users recognize, diagnose and recover from errors

Error messages should be expressed in plain language, precisely indicate the problem and constructively suggest a solution.

#### 10. Help and documentation

Even it is better if the system can be used without documentation, it may be necessary to provide help and documentation. Should be easy to reach, list concrete steps and should not be too extensive.

### 2. Predictive User performance models

Way of evaluating products or design without directly involving users. Estimated of efficiency of systems for different tasks.

We use GOMS to model knowledge about the system and cognitive processes involved when users interact with systems.

We use KLM to provide numerical predictions to performance and estimate chains of operations.

#### GOMS model

##### Goals

The state the user wants to achieve.

##### Operators

Cognitive processes and physical actions needed to attain the goals (mouse click etc.)

##### Methods

Procedures for accomplishing the goals, drag mouse over search field, type in term, press go etc ...

##### Selection Rules

Decide which method to select when there is more than one.

Goms example:

Goal: delete a word in a sentence

Method for goal of deleting a word using menu option:

- Step 1. Recall that word to be deleted has to be highlighted
- Step 2. Recall that command is 'cut'
- Step 3. Recall that command 'cut' is in edit menu
- Step 4. Accomplish goal of selecting and executing the 'cut' command
- Step 5. Return with goal accomplished

#### Keystroke Level model (KLM)

Mesasures and compares execution times.

Operator name	Description	Time (s)
K	Pressing a single key or button	0.35 (average)
	Skilled typist (55 wpm)	0.22
	Average typist (40 wpm)	0.28
	User unfamiliar with the keyboard	1.20
	Pressing shift or control key	0.08
P	Pointing with a mouse or other device to a target on a display	1.10
P <sub>1</sub>	Clicking the mouse or similar device	0.20
H	Homing hands on the keyboard or other device	0.40
D	Draw a line using a mouse	Variable depending on the length of line
M	Mentally prepare to do something, e.g. make a decision	1.35
R(t)	System response time – counted only if it causes the user to wait when carrying out his/her task	t

#### Predictive models strengths and weaknesses

- Relatively easy to perform comparative analysis for different interfaces and prototypes, specifications.
- Can only model high-level tasks, involving small set of high routine low level tasks
- Only valid for predictable/expert behavior (no multi-tasking, fatigue, learning effects etc)

### 5 Evaluations and Experimental Design

*Formative* early in the design process, sanity checks that we're building the right thing. *Summative* to check if we improved upon our last iteration, does it work better than other solutions?

#### Quantitative Evaluation Methods

Ensure certain level of quality, comparesolutions objectively, attain a scientific statement.

#### Primary Usability Metrics

A **usability metric** reveals something about the interaction between **the user** and **the thing**:

**Effectiveness**

being able to complete a task

**Efficiency**

amount of effort required to complete the task

**Satisfaction**

degree to which the user was happy with his/her experience while completing the task

these metrics can help answer these critical questions:

- Will users like the product?
- Is this new product more efficient than past products?
- How does the usability of this product/version compare to others?
- What are the most significant usability problems with this product?
- Are improvements being made from one design iteration to another?

#### Cause and Effect

We want to identify clear causal links. Cause precedes effect, they need to correlate and other explanations have to be ruled out. Isolate causality by controlled experiments. Alter design with suspected cause absent (control) and present (experimental condition). All other conditions should be identical.

## Quasiexperimentell — Observational

We observe that independent variable and dependent variable are highly correlated, but did not control for anything (for instance participation in exercises and final exam grade).

## Experimental — Controlled

We randomly assign students to exercise and no exercise condition, then we controlled for other variables and results implies causality.

### characteristics of Empirical Methods

- Objectivity
- Reproducibility
- Validity (internally and externally)
- Relevance

For instance threat to external validity is over-use of specific participant groups (only psychology or cs students).

### The experiment

Independent variables affect the dependent (measured) variables through experiment.

Variables can be categorical, ordinal (ordered discrete), or cardinal/interval (continuous) data.

### Designing an empirical study

1. What is being compared? (which Independent variables)
2. What are they being compared in? (dependent variables, metrics)
3. What else is being varied? (extraneous variables to control/eliminate)
4. Relevance

Look at slide set 5 for various examples.

### More complex comparisons

Different experimental designs possible: *Within subjects*: Everyone does everything. *Between subjects*: Only one condition per group.

### Latin Square Counterbalancing

full randomization can lead to huge experiments (e.g.,  $6! = 720$ )

Latin square design reduces number of experimental orderings

- total number of experimental conditions is the square of the number of treatments
- each treatment appears once and only once in each row and column

A	B	C	D	E
D	E	B	A	C
B	C	E	D	A
E	A	C	B	D
C	D	A	E	B

### Latin Square Example for 5

first row in alphabetical order  $\Rightarrow A B C D E$

subsequent rows – shift letters one position

A B C D E	2	C D E A B	A B D C E
B C D E A	4	A B C D E	D E B A C
C D E A B	1	D E A B C	B C E D A
D E A B C	3	B C D E A	E A C B D
E A B C D	5	E A B C D	C D A E B

Then: randomize the order of the rows: i.e., 2 4 1 3 5

randomize the order of the columns: i.e., 4 3 5 1 2

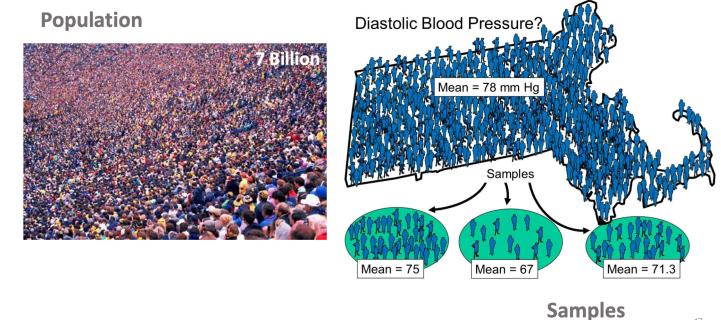
## 6 Statistical Analysis

### Data Collection

Important:

- Choose representative sample
- Form hypothesis to make assumptions testable
- collect data to test Hypothesis
- collect all available data (better too much)

### Population vs Sample



### Generalizability

Results should be valid for all people. Participants should be representative of population. Look at relevant factors, such as Age, Gender, Occupation.

### Hypothesis testing

Effect size is difference in the means of  $H_A$  and  $H_0$ . It is unknown a-priori and hence we don't know how to show the threshold for acceptance. Therefore instead of showing  $H_A$  is true, we show that the obtained data is incompatible with  $H_0$ .

### Descriptive statistics and validation

How should data be validated?

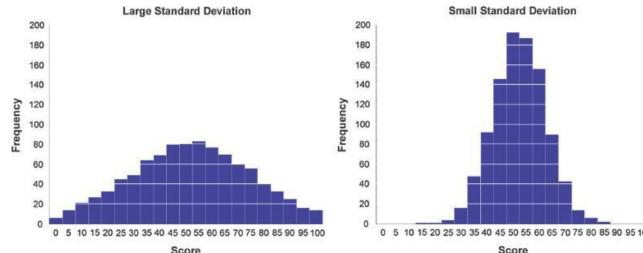
#### Mean

Least distance to all other data points. Good representation of data points piled together. Bad representation if some data points are extreme values (outliers). Doesn't make sense if we divide through categorical or ordinal data.

#### Median

is robust against outliers. The number at the middle of the ordered data points. Natural choice to represent ordinal data.

#### Distribution



### Confidence Interval (CI)

Interval in which we are very sure that our true values lie in. We mostly choose 95 percent of values to lie within this interval if often replicated. Confidence interval of mean difference (two samples)

### Analysis

Bayesian quantitative approach no covered in this course, also not qualitative analysis methods.

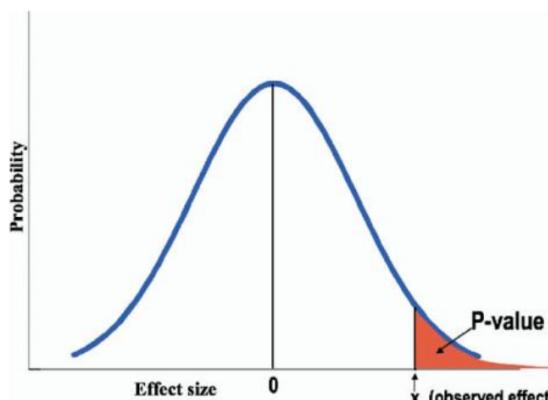
### Frequentist Approaches

#### Hypothesis testing

We assume  $H_0$  to be true. The lower our p-value the less likely that  $H_0$  is true and  $H_A$  is true. P-value indicated how compatible the data to which hypothesis is.

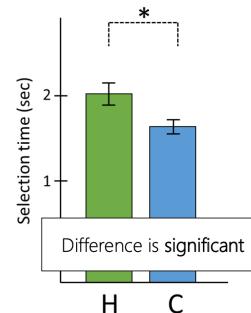
#### P-Value

P-value is probability of observed data if  $H_0$  were true.

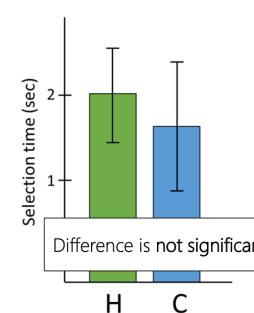


### Alpha-Level

Threshold to determine if p-value is lowe enough. Usually  $\alpha = 0.05$ . In medicine even lower. If p-value is larger than  $\alpha$  this does not mean that  $H_0$  is true!



Significant implies that in all likelihood the difference observed is due to the test conditions (H vs. C).



Not significant implies that the difference observed is likely due to chance.

### Errors

Type I error: Effect was found, but no effect in reality (False Positive).

Type II error: No effect was found, but effect exists in reality (False-Negative).

### Degrees of Freedom

Number of values that are free to vary. Number of observations ( $n$ ) minus the number of parameter estimates. For one-sample t-test:

$$v = n - 1$$

### Independent vs dependent samples

Independent: One subject only exposed to one condition (use different subjects for differen conditions). Also referred to as Independent measures or means.

Dependent: Same subject exposed to all conditions (Within subject design). Also referred to as matched pairs or paired samples.

### Parametric vs. non-parametric tests

Non-parametric do not assume specific distribution. Assume equal spread of group samples. Less statistical power. Type II error more likely.

Examples: Chi-Square, Mann Whitenes, Wilcoxon's signed rank test, Kruskal Wallis, Friedman

Parametric tests assume gaussian distribution and homoscedasticity (equal variances). More power!

Examples: one-sample t-test, two-sample t-test, paired-sample t-test, one-way/factorial ANOVA, repeated measured ANOVA.

### A/B Testing

Common example as in our case: Change one categorical independent variable with two levels (A and B) and measure one interval dependent variable. In our case task execution time.

### Independent t-test

Checks if two means are reliably different from each other.  $t = (\text{variance between groups}) / (\text{variance within groups})$ .

Large t means different groups ( $H_0$  refuted).

### From t-value to significance

T-values lead us to our p-value over degrees of freedom in standardized tables. T-distribution depends on sample size (degrees of freedom). Its a distribution of t-values of a population where the null hypothesis is true.

### ANOVA analysis of Variance

Use this if independent variable /factor has three or more levels. One-way ANOVA is used for data with one factor and multiple levels. Factorial ANOVA is used for data with multiple factors and levels. Does not tell us which levels are different.

### Effect size

Statistical significance does not mean that the measured effect is meaningful. So we need a standardized effect size. We use Cohen's d, Pearson's correlation, odds ratio.

Cohens' d is a standardized mean difference between the samples. Depends on the field.

$$\text{Cohen's } d = \frac{\text{mean}(A) - \text{mean}(B)}{\text{mean}([\text{std}(A), \text{std}(B)])}$$

### Power analysis

Compute min. number of participants to achieve desired effect. Can be calculated from

- prob. of finding an effect that is not there ( $\alpha = 0.05$ )
- prob. of finding an effect that is there ( $1 - \beta = 0.8$ )

- the desired effect size (HCI d = 0.8)

## Software for statistical analysis

- SPSS
- Python
- R
- etc.

## Reporting

### Writing up the results

To compare the effect of the independent variable on the dependent variable, we conducted a statistical test as data [not] meets assumptions

With condition A, ... (M = XX, SD = X). With condition B, (M = XX, SD = XX).

The mean difference between the two groups was statistically [not] significant; DOF of test, p-value, etc.

These results indicate that condition A was ... than condition B.

Which variables?  
Which statistical test?  
Which assumptions?

How do the samples look like?

How do differences look like?

What do differences mean?

The humans perception, memory and motor system can be applied to estimate execution time, error rates, training effects for simple stimulation /reaction interactions and system parameters.

### Information Processing pipeline

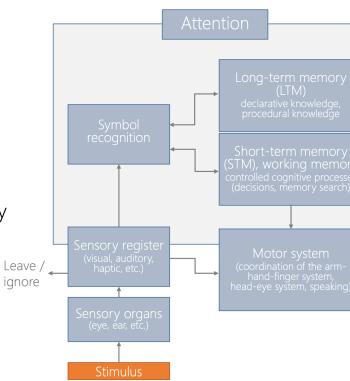
#### Input – Perception

- Visual system
- Auditory system
- Haptic system

#### Processing – Cognition and Memory

- Sensory memory
- Short-term memory
- Long-term memory

#### Output – Motor System



We look at three main processors with associated memory.

#### Perceptual System

Containing sensors and buffers.

#### Cognitive System

Containing working memory and content symbolically coded

#### Motor System

Contains movements.

Each processor has associated runtime. Overall runtime is sum of these.

### Perception (Visual System)

#### Anatomy of human eye

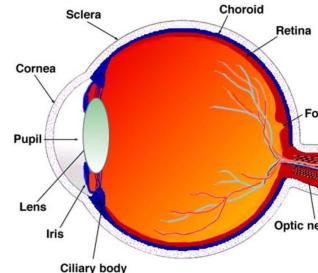
light travels through:  
cornea → crystalline lens → retina

iris controls amount of light

retina "decodes" light through photo receptors
 

- rods (low-light vision)
- cones (color vision)

optic nerve transmits processed light to visual cortex



Rods are very light sensitive and have a slow response time. Are located in the periphery of the fovea. 120 million per eye, have maximum sensitivity at 500nm.

Cones are fast in responding and concentrated at the fovea. 6 million per eye. Three types for blue (S type, 420nm), green (M type, 534nm) and red (L type, 564nm).

#### Visual Field

Sharp vision within 2 degree radius of fovea. Fine detail. Peripheral vision has decreased visual acuity with distance from fovea. Horizontal visual field is 60 degrees nasally and 90 degrees temporally. Vertical visual field is 60 degrees up and 70 degrees down.

Useful field of view is rather small (1-4 degrees for high character density and max 15 degrees for low character density.) We use this in Foveated Rendering to reduce details in the outer parts (for instance with eye tracking).

#### Eye movement

Saccades are repositioning of fovea. Take around 30ms with an amplitude of max 600 degrees per second. Perception is greatly decreased.

Fixations are dwelling on one point. Its between saccades. It takes around 90 percent of the visual time. Take around 150 to 600 ms.

Gaze movements are context dependent of foreknowledge, attitude, task and predisposition.

#### Reading

Reading is a sequential loop of fixation and saccades. In average around 230ms fixation and 30ms saccades. On average around 300 WPM reading speed.

#### (Visual) Attention

We have great gaps in our perception. Interpretation is much sparser than one might assume. Perception of objects requires lots of attention. Attention has to be directed. Perceptual processor receives and buffers signals. One buffer per sensory channel. Perception time is around 100ms (ranging 50-200ms).

#### Bloch's law

$$R = I * t$$

Where R is response, I is intensity and t is exposure time. For  $t \geq 100\text{ms}$ , we assume R constant. As a consequence we have limits on frame-rates (min 10Hz).

## Cognitive Processor

Connects perceptual system to motor system. Learning, retrieval of facts, decision making, problem solving etc...

Processing time is around 70ms (25-170). Operates on chunks of information. For instance age, parts of a phone number.

## Short term memory

Working memory, responsible for intermediate products of thinking and representations of perceptual system. Holds activated item from long term memory. Capacity is limited to 5-9 units (augmented by LTM). Pure capacity is around 2-4 units. Decay rate and capacity can be varied depending on strategy etc. but decreases strongly with increased items.

## Long term memory

Declarative (facts etc.) and procedural (how to do stuff) parts. Practically unlimited capacity with no decay time. Retrieval depends on associations with for instance external stimuli. It is fast-read, slow-write.

## Designing for memory

We try to design for memory through grouping of related functionalities and use familiar structures. We also use recognition instead of recall.

## Motor Processor

The average processing time is the sum of time needed for the perceptual, cognitive and motor processor. We differentiate between an open (no perceptual control, motor processor takes around 70ms) and a closed loop (perceptual system controls movement, ca 250ms).

## Fitt's Law

Models throughput in aimed movements such as reaching for a control in the cockpit or clicking on icons with a mouse. Is very powerful and widely used. Holds in many circumstances, also under water and intoxicated. Allows for comparison among different experiments.

Originally the task was to touch the centerplate with a pencil, without touching the error plate on the sides. Generally

the task is to predict the time to hit a target as a function of distance and size.

## Index of difficulty

$$ID = \log_2(2D/W)$$

## Index of Performance or Throughput

ID = information (nr of bits) required to specify movement (amplitude within given tolerance) IP is index of performance.

$$IP = ID/MT$$

(is in bits/sec) Depends on input device and limb. Movement time MT

$$MT = a + b * ID$$

$$MT = a + b * \log_2(2D/W)$$

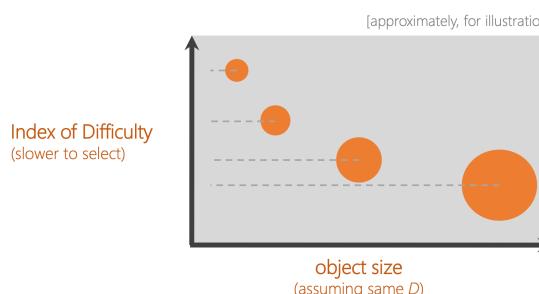
In the end we can use the different MTs to estimate a regression on ID and MT (estimate a and b of line).

## Fitt's Law implications

We find that doubling the distance adds roughly a constant to execution time (Logarithmic nature of the law). Doubling the target width is roughly equal to halving the distance (implied by D/W term in the formulation).

$$ID = \log_2\left(\frac{2D}{W}\right)$$

Logarithmic, i.e., assuming same D, there is a bigger benefit to increasing size of small targets than large targets



## Fitt's Law in practice

We can add the last pixel of buttons on the left side, to increase to effective Width of "almost infinite".

Larger fields can be clicked more easily.

## Application: Compare input devices

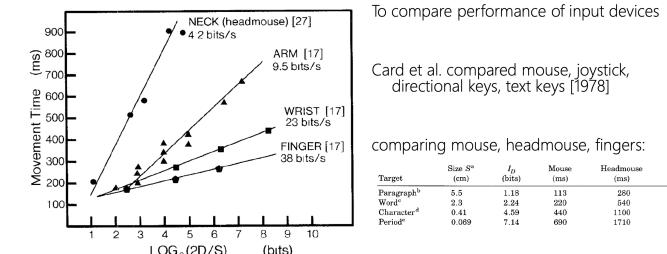
Compare mouse, trackball and stylus in speed. Use pointing and dragging as actions. This corresponds to finding a and b in the formula for MT. We can then use this information to design an "optimal" UI.

## Limitations of Fitt's Law

Fits law does not:

- consider body asymmetries (right vs. left hand flexion vs. extension)
- address parallelization strategies (use multiple finger, hands)
- include any cognitive factors (reaction time, visual search time etc.)

## Bandwidth



Performance of use depends on human (bandwidth of muscle groups), application (precision requirements of the task) and device (effective bandwidth of input device).

## From Model Human Processor to Fitt's Law

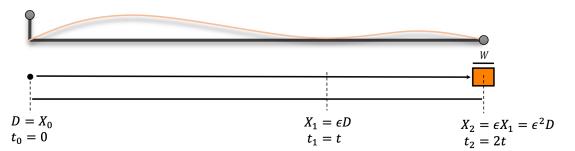
### Visual and Proprioceptive Feedback Loop

First we observe hand position, then we plan the movement, we perform the hand movement and finally assess the error to expected position. This is a loop and gets repeated until desired movement is finished.

Assumptions: movement consists of multiple ballistic sub-movements of *constant* time  $t$  and *constant* error  $\epsilon$

Deterministic iterative corrections model

- Movements longer than 200 ms are controlled by visual feedback



We know from MHP that one cycle through all processors is around 300ms. If n is the times we go through loop, the final time then is

$$n \times (\tau_p + \tau_c + \tau_M)$$

After the first cycle we have:

$$X_1 = \epsilon X_0 = \epsilon D$$

In the second cycle:

$$X_2 = \epsilon X_1 = \epsilon(\epsilon X_0) = \epsilon^2 D$$

$n^{th}$  cycle :

$$X_n = \epsilon^n D$$

We stop the movement when:

$$\epsilon^n D \leq \frac{1}{2} W$$

We solve for n:

$$n = -\log_2 \left( \frac{2D}{W} \right) / \log_2 \epsilon$$

We insert into formula for movement time:

$$MT = n \times (\tau_p + \tau_c + \tau_M)$$

⇒

$$MT = \frac{\tau_p + \tau_c + \tau_m}{-\log_2 \epsilon} \cdot \log_2 \left( \frac{2D}{W} \right)$$

$$MT = I_M I_D$$

$$I_M = \text{Index of motion} \left( \frac{\text{sec}}{\text{bits}} \right)$$

## 8 Visual Perception

### Gestalt principles

Gestalt psychology was founded in the 1920s by Max Wertheimer and others. It is about the perception of groups, patterns and objects.

#### four key principles

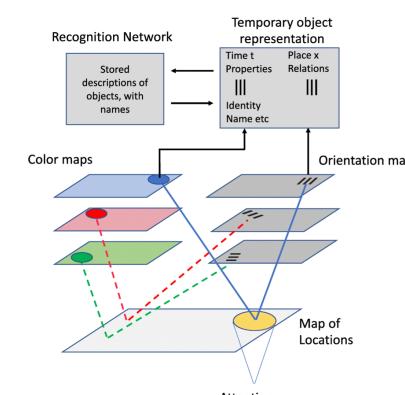
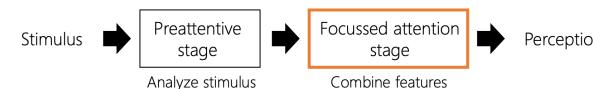
- Emergence
- Multistability
- Eification
- Invariance

#### laws of grouping

- Proximity (close objects belong to group)
- Similarity (similar appearance belong to group)
- Closure (humans prefer to see complete figures)
- Symmetry (symmetric objects form groups around the center)
- Figure and ground (users tend to separate images of foreground and background)
- Continuity (Objects that intersect are perceived as individual objects)
- Past experience (Based on past experience group objects together)

### Feature integration theory

Availability of visual information is limited. Full visual acuity is only available in foveal area. Peripheral vision provides limited information. This is why FIT suggests stimuli that are registered early and automatically.



Theory is based on the process of selective attention. Is useful but certainly limited in certain aspects. FIT primarily concerns bottom-up activation. Top-down activation through memory and expectation.

### Selective Attention

There is an ongoing debate about Early / Late selection. The early selection model has been proposed earlier and mainly relies on the idea of an early "bottleneck" in the attentional process given by perception. It also assumes that focused attention can prevent distractor processing at an early stage.

Late selection was proposed later and assumes unlimited perception and the automatic discrimination of relevant and irrelevant stimuli. It assumes that later processes such as memory or behavior are the processes with selected attention.

### Perceptual Load Theory

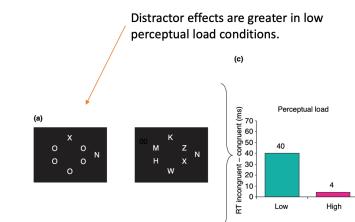
Sees perception as a process with limited capacity. This is in line with the early selection views. PLT also assumes that automatically all stimuli are processed until capacity is filled.

#### Example experiment on PLT

Cognitive load and capacity is directly related with response time and users' ability to react to visual stimuli.

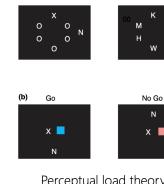
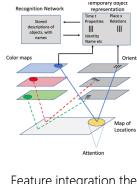
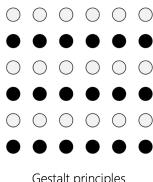
Typical setup of experiments

1. User is asked to find a target, X or N, *within the circle*.
2. Another stimuli, X or N, is also presented as *peripheral distractors* outside the circle.
3. The letters (M, H, W, Z, K) or little symbols (o) in the circle vary the cognitive load.



### Takeaways on PLT

Users ability to react to stimuli is related to its context. High load leads to more focus and less distraction. Low load leads to quicker distraction.



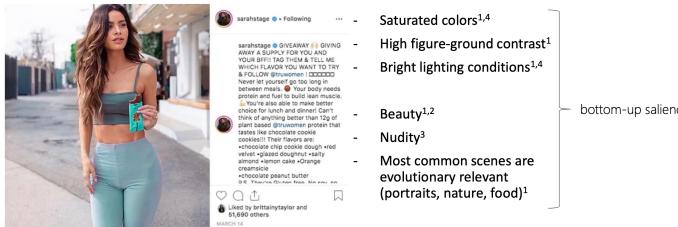
## Visual Saliency

The context of objects popping-out as pre-attentive for selection. Assumes that feature maps are computed in parallel and combined. The computed maps yield a saliency map. Assumes that the "Winner-takes-it-all". Assumes that this sequential processing is based on inhibition of return.

Example is given by an experiment where different skins are compared and snake skin resulted in significantly higher brain activity measured over EEG.

With visual saliency we can predict users' gate and importance. It is mainly bottom-up and therefore feature based. Top-down saliency is challenging, however task and load influence the saliency.

If there is too many competing features, clutter will occur.



## Visual Search

The process that decides where humans look next.

1. Guided Search (rules exist on priorities for items or areas in the scene)
2. Bounded rationality (selection of actions based on expected utility under uncertainty)

### Guided Search

1. Calculate the distance (eccentricity) to the current fixation location for each item

2. Given eccentricity decide which items and features are available to visual representations
3. Calculate bottom-up saliency for each item
4. Calculate top-down saliency for each item
5. Sum up bottom-up and top-down activations and select the ones with highest activation

### Bounded Rationality

Assumes that humans take the action with satisfactory expected utility given their constants.

Simply put: Humans takes the **action** with satisfactory **expected utility** given their **constraints**.

1. calculate the distance (eccentricity).
2. decide which items and features are available.
3. calculate the bottom-up saliency
4. calculate the top-down saliency
5. The item with the highest activation will be attended next.



fundamentally dissimilar agents-both in perception and processing.

"It's a transducer from the physical properties of the world into logical values of the application."

## Fitts' Law in 2D

1D

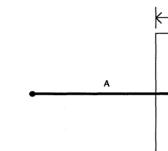


Figure 1. Fitts' law paradigm. The law is inherently one-dimensional since target amplitude ( $A$ ) and width ( $w$ ) are measured along the same axis.

2D

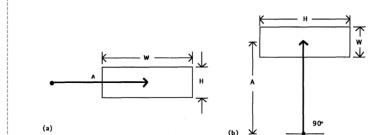


Figure 2. Fitts' law in 2D. The roles of width and height reverse as the approach angle changes from 0° to 90°.

What is target width for 2D movement?

**Variant 1**  
Length of path part that is inside rectangle, i.e.,  $W'$  ("W-prime") inside rectangle in picture

**Variant 2**  
Smaller value of  $W$  and  $H$ , i.e.,  $\min(W,H)$

According to MacKenzie et al., both variants (1,2) are more suitable than using  $W$  (without prime), but there are no significant differences between the variants (1,2).

## Properties

### Direct / indirect input

- Direct: Touchscreen, "grasping" virtual 3d objects
- Indirect: Mouse movement translated to cursor position (virtual cursor can directly/indirectly manipulate virtual content)

### Absolute / relative

- Absolute: Position of input mapped to position of output (e.g. drawing tablet)
- Relative: Change of input position mapped to change of output position (e.g. mouse)

### Position control / rate control

- Manipulate position of something (e.g. mouse cursor) versus its velocity (e.g. thumbstick)

### Degrees of freedom

- Examples: only 2D position along surface (2 DoF), 3D position and rotation in mid-air (6 DoF), or other combination (3D position + rotation around one axis : 4 DoF)

*Isotonic / elastic / isometric*

- Movable (isotonic e.g. mouse) vs. movable but goes back to neutral position (elastic, e.g. joystick) vs. immovable (isometric, sense force only e.g. lenovo red dot)

## Performance/Bandwidth

The performance depends on the human (bandwidth of muscle groups connected to input device), the device (effective bandwidth of input device) and application (precision requirements of the task).

## Effectiveness

- Pointing speed
- Pointing precision
- errors
- Time to learn
- Time to grasp device
- User preference
- Desk footprint
- Cost

## Design Space by Card et al

Input device as six-tuple: (M, In, S, R, Out, W)

- M: Manipulation operator
- In: Input Domain
- S: Current state of device
- R: (Resolution) Mapping from input domain to output domain
- Out: Output domain
- W: Additional aspects of how device works (input lag etc.)

## Possible manipulation operators **M**

	Linear	Rotary
Position Absolute Relative	Position P Movement dP	Rotation R DeltaRotation dR
Force Absolute Relative	Force F DeltaForce dF	Torque T DeltaTorque dT

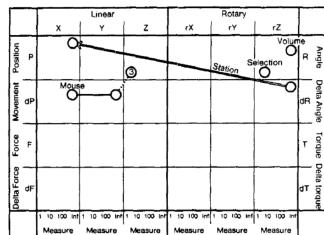
## Composition operators

- Merge composition: e.g. sensed X-Y movement of mouse merged into 2D input

- Layout composition: Separate independent inputs on a device (e.g. independent buttons or wheels on mouse)
- Connect composition: Output of one device/sensor mapped into input of another (e.g. physical mouse is input for virtual screen cursor). In this context virtual cursors count also as input devices.

## Card's Graphical representation

Example from Card et al: 3-button mouse and radio station



## Input Decoding

### Touch Input

Issues with touch: It's noisy and touch area larger than the target. Also visual occlusions. Mobility increases accuracy issues.

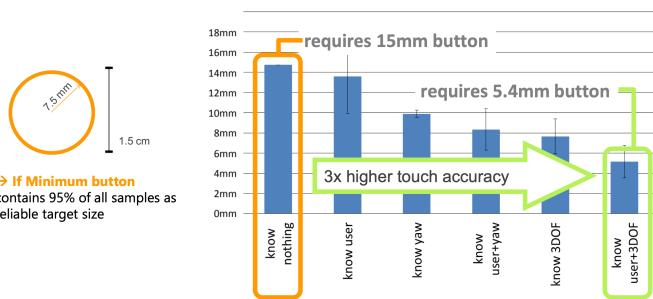
Task: Hit target on touch screen (repeatedly)

Independent Variables: Yaw, roll, pitch, user (mental model)



We record every trial as a dot at the touch location. Without influence of independent variables should result in circles. If the locations fall into clusters we can compensate if condition is known.

### Minimum Touch Input Size



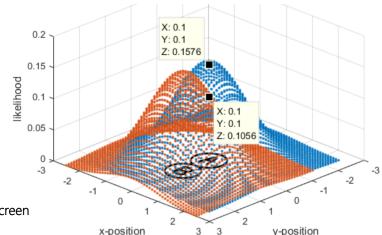
## Representing Input

$$P(y|x) \text{ Probability of message } y \text{ given signal } x$$

$$= \frac{P(y|x)}{P(x)} = \frac{P(x|y)P(y)}{P(x)}$$

Conditional probability  
Bayes' rule

A concrete example for a single letter input:  
 $P(y|x)$  is the probability of letter 'a' or 'b' given a screen coordinate in 2D



→ Use for **statistical decoding** of **message sequences**

## Sequence decoding

Given an input (touch, key), predict most likely next message.

$$P(y|x) = \frac{P(x|y)P(y)}{P(x)} \quad \leftarrow \text{Posterior distribution}$$

Most probable message →  $\hat{y} = \arg \max_y \frac{P(x|y)P(y)}{P(x)}$

$$\hat{y} = \arg \max_y [P(x|y)P(y)] \quad \leftarrow \text{maximize conditional probability of the message given the signal}$$

$$\text{hypothesis} = \arg \max_{\text{hypotheses}} [\text{likelihood model} \cdot \text{prior model}]$$

An example would be to investigate noisy sequences of input and identify the most likely sequence of intended presses. Observation would be the 2D screen coordinates of tap and the observation sequence are the time-ordered observations.

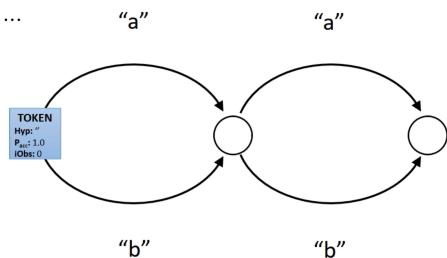
A token in this context would be a datastructure containing the accumulated probability of hypothesis.

$$\text{Acc\_Prop}_{n+1} = \text{Acc\_Prob}_n * \text{prior} * \text{likelihood}$$

### Simple sequence decoding

One token per hypothesis per observation.

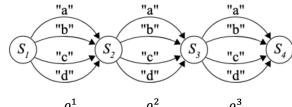
- $k^i$  tokens ...



### Substitution-only decoder

#### Input

- set of  $k$  symbols that can be recognized (i.e.  $k$  letters)
- a series of 2D coordinates (observation sequence)  $O = \{o^1, o^2, \dots, o^n\}$
- language model (probabilities)



#### Token propagation rules

- Propagate token for every hypothesis for every observation
- Update token's probability: posterior = likelihood x prior

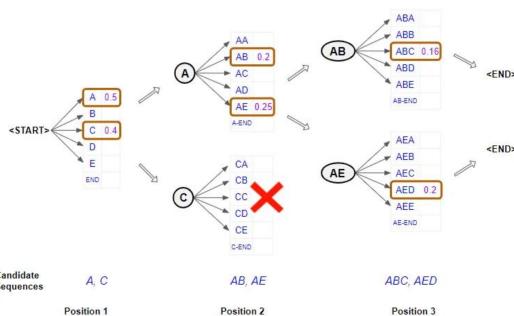
### Breadth Pruning

we have an infinite search space but only a few plausible hypothesis. We prevent propagation of unlikely tokens.

#### Rules of beam Pruning:

- Only propagate a token if its probability is among the  $n$ -best probs for the observation so far
- If the new prob of the observation is among the  $n$ -best then update the list of tokens to propagate

Threshold is also known as beam size.



### Language models

Probabilities for the decoder come from Language models. Language models are the probability of individual words or word sequences. A vast amount of letter combinations is unlikely to be written. These models capture valid letter and word sequences and assign them probabilities. These probabilities can be leveraged to infer or predict what users want to write, based on what they have already written.

The simplest models are uni- or bigrams. (Unigram contains one token only and bigrams obviously two).

### Trigram Model

The **trigram language model** is a second-order Markov process. This model defines  $P(w|u \cdot v)$  for any  $w, u, v \in V$  where  $V$  is some vocabulary of words|letters. For a sentence  $s = w_1 \cdot w_2 \cdot w_3 \cdot \dots \cdot w_n$  we can compute the probability  $P(s)$ .

$$\begin{aligned} P(w_1 \cdot w_2 \cdot w_3 \cdot \dots \cdot w_n) &\sim= \\ P(w_1) * \\ P(w_2 \cdot w_1) * \\ P(w_3 \cdot w_1 \cdot w_2) * \\ P(w_4 \cdot w_2 \cdot w_3) * \\ \dots \\ P(w_n \cdot w_{n-2} \cdot w_{n-1}) \end{aligned}$$

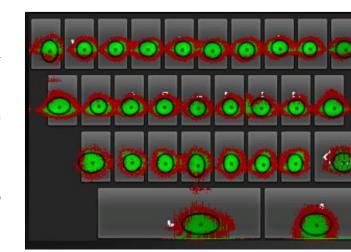
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The conditional probability  $P(w|u \cdot v)$  is typically estimated via some form of counting and smoothing (e.g. linear interpolation of unigrams), bigrams (e.g.  $u \cdot v$ ) and trigrams ( $u \cdot v \cdot w$ ).

Smoothing is necessary to deal with **sparseness** which can occur because many trigrams  $u \cdot v \cdot w$  and even bigrams  $u \cdot v$  may not occur in the training data.

Time complexity for each word encountered in training is **constant**, so training is usually **fast**.

### Real example: bivariate Gaussian keyboard model



[Image: Henze et al. CHI '12.]

$$P(K|T) = \frac{N(T|\mathcal{C}_K, \Sigma_K)}{\sum_1^n N(T|\mathcal{C}_K^n, \Sigma_K^n)}$$

$N(\dots)$  is the bivariate Gaussian distribution

$T$  is the touch position

$\mathcal{C}_K$  and  $\Sigma_K$  are the mean and covariance of the touch distribution for key  $K$

### Application Examples

- Predictive text input
- Text input beyond screens
- Accessible mixed reality

(Check slides if you want to see more on these).

## 10 Computational Design

The main idea of this chapter is to use models and algorithms to help design and optimize interfaces. The chapter will contain:

- Modeling task as combinatorial optimization problem
- User models as cost / goodness functions in optimization
- The assignment problem and applications in HCI
- Examples

Example: 50 different items yield  $50!$  options to create menus.

To evaluate a menu we can use:

Time to move to an element  $i$ :

$$t_i = a + b \log_2 \left( \frac{A_i}{W_i} + 1 \right)$$

Average time to operate a menu:

$$T = \sum_i p_i t_i$$

### Design as Search

As a goal we want to find the best design decision for given objectives.

Some benefits of using algos in design:

- Efficiently search large solution spaces
- Systematic, rigorous process
- Improved quality and reliability
- Guarantees for goodness of outcomes

We want to find optimal  $x \in X$  where  $X \in \mathbb{K}^n$  which maximizes  $f(x)$ . So  $X$  is the set of all feasible solutions.

### Formulate optimization problem

- The design space (variables, constraints)
- Objective functionality
- Way to solve problem (solver)

### Design Space

A combination of all design variables forms the design space. Each variable represents an open decision (usually discrete):

- Boolean(e.g. show label)
- Integer(e.g. color)
- Categorical(e.g. type of element)
- Continuous(e.g. color value)

As not all combinations yield a feasible design we need to introduce constraints.

Decision variables:

$$x_{ik} = \begin{cases} 1, & \text{if command } i \text{ assigned to slot } k \\ 0, & \text{otherwise} \end{cases}$$

Design space:

$$X = \{\mathbf{x} = (x_{ik}) \mid i, k = 1 \dots N, x_{ik} \in \{0, 1\}\}$$

Constraints (feasible space):

$\sum_{k=1}^n x_{ik} = 1 \quad \forall i = 1 \dots N$ , where each command is assigned to one slot.

$\sum_{i=1}^n x_{ik} = 1 \quad \forall k = 1 \dots N$ , where each slot is assigned to one command.

### Objective Function

Assign a score to each solution in the design space. Goal is to find the solution that maximizes or minimizes the objective function. Can be interpreted as quality indicator of UI.

We can find an objective function in different ways.

- Math model
- Machine-learning model
- Simulation-based model
- Look up tables from empirical data
- Heuristics, guidelines, best-practices

Example: Minimize average selection time (linear assignment problem):

$$\min \sum_{i=1}^n \sum_{k=1}^n p_i \cdot t_k \cdot x_{ik}$$

Where  $p_i$  is prob of item  $i$ ,  $x_{ik}$  the constraints and  $t_k$  the time to move to slot  $k$  from the top. We call  $x_{ik}$  the decision variables.

### Optimization Methods

#### Mathematical, Exact Methods

Linear or (Mixed-) Integer Programming, Branch and Bound methods

- + Explicit bounds and guarantees optimality
- + Fast standard solvers available
- - Objective function in closed mathematical form
- - Problem formulation might be hard to set up

#### Heuristic approximation algorithms

Simulated annealing, Genetic algorithms, Biology inspired algos

- + Programmatical description
- + Standard implementations available (Scipy, Optimization Toolbox Matlab etc.)
- + Flexible
- - No bounds or guarantees on global optimum
- - Can have many params

### Assignment Problem

Assign items from Set A (e.g. menu items) to items in Set B (e.g. menu slots).

#### Quadratic Assignment Problem

Similarity between commands:  $s_{ij}$

Distance between menu slots:  $d_{kl}$

$$\min \sum_{i=1}^n \sum_{j=1}^n \sum_{k=1}^n \sum_{l=1}^n s_{ij} \cdot d_{kl} \cdot x_{ik} x_{jl}$$

Pairs of command-slot assignments  
The more similar the closer together

Is an np hard problem. Decision cost:  $s_{ij} * d_{kl}$ . The second part  $x_{ik} * x_{jl}$  is quadratic in the number of decisions.

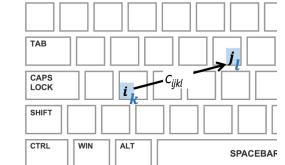
### Example: The letter assignment problem

Question: Find best assignment of letters to keys on a smartphone to allow the fastest typing. Apply constraints: Each key assigned to exactly one letter, each letter assigned to exactly one key.

### Design Space

n characters	-	$i, j \in \Sigma$
m keyslots	-	$k, l \in S$

$$x_{ik} = 1 \text{ if character } i \text{ is assigned to keyslot } k, \\ x_{ik} = 0 \text{ otherwise}$$



Goal: Find the assignment of characters to keyslots that minimizes the cost of typing (special characters)

The goal was then to minimize the motor performance (average time to move between special characters and letters) and Ergonomics (minimize frequent extreme movements of wrist and fingers for special chars). For Intuitiveness minimize the distance between similar special chars and also their visual similarity. Familiarity refers to redesign similar to known preferences.

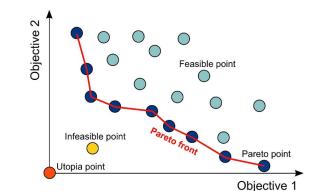
### Multi-objective optimization

Goodness of user interface is determined by many aspects.

- Performance
- Ergonomic and Fatigue
- Error prob.
- Mental workload
- learnability
- Accessibility
- Subjective experience
- etc.

- Weighted sum approach
- Pareto optimization
- Hierarchical optimization
- ...

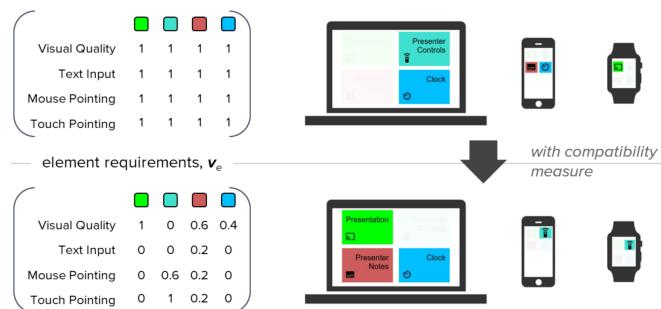
$$w_1 \hat{f}_1 + w_2 \hat{f}_2 + w_3 \hat{f}_3 \dots$$



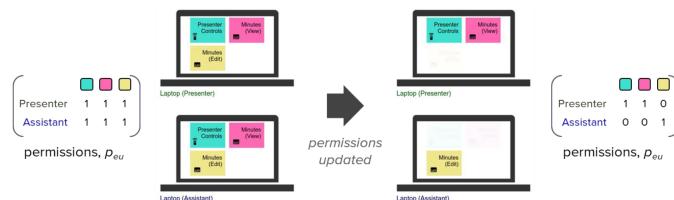
## Combinatorial Optimization for User Interface Adaption

Optimize the UI to accomodate changes in environment, cognitive state, abilities, task, technical capabilities etc. Use different objectives such as optimize for quality and completeness.

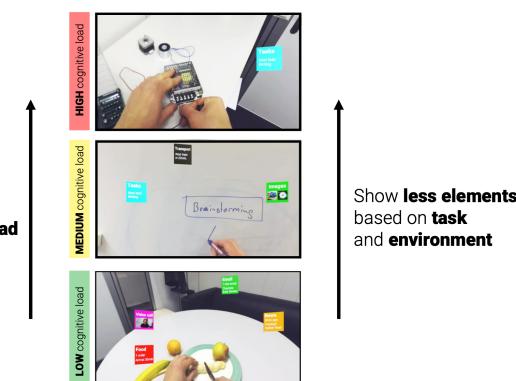
### Element device compatibility



### User roles



### Cognitive Load



The idea then is to include cognitive load, cognitive capacity and cognitive cost to the objective function.

### Optimize for environment

The idea is to optimize for different environments, e.g. screen placement, number of virtual screens etc. We include interaction modality, occlusion avoidance and temporal consistency into the objective function.

This can be done through assigning voxel containers to objects and surfaces. The objective would be to optimally assign elements to containers.

$$x_{e,c} = \begin{cases} 1, & \text{if } e \text{ is assigned to } c \\ 0, & \text{otherwise} \end{cases}$$

$$\operatorname{argmax}_{e,c} (w_t \cdot T + w_v \cdot V + w_i \cdot I)$$

Temporal consistency      Occlusion avoidance      Interaction modality

### Temporal Consistency

$$T = \frac{1}{N_e} \left( - \sum_e \sum_c \|p_c - p_e^i\| x_{e,c} \right)$$

container position      element input position

### Interaction Modality

$$I = \frac{1}{N_e} \sum_e \sum_c (w_t Q_t^c + w_{elb} Q_{elb}^c + w_m Q_m^c + w_d Q_d^c) x_{e,c}$$

touch      elbow-rested      mid-air direct      distant

metrics support placements for respective modality

New contexts might introduce physical constraints that may render prior interface layouts unusable.

## 11 Haptics

### Importance of haptics

Haptics is the study of touch, force and tactile feedback in human-computer-interaction. Haptics feedback is everywhere and could be used for gaming, robotic surgery, education and many more.

- Enhances user experience and engagement
- Enables more intuitive and natural interactions
- Addresses limitations of visual and auditory feedback
- Vital for accessibility and inclusion

### Interaction benefits

- Increased accuracy and speed
- Reducing errors
- Eyes Free interaction
- Proprioceptive

### Tactile

All about vibrations and textures.

- Sense of touch
- Goal: Stimulate skin in a programmable manner to create desired set of sensations
- Tactile feedback is generated by tactile device
- Skin based
- Examples: Vibration, pain, pressure, temperature
- Used in touchscreens, tactile displays and VR

### Vibrotactile

- Subset of tactile
- Relies on vibrations to convey information
- Common in mobile devices, notifications and wearables

When designing actuators its important to consider that different cells are in different parts of hand. They have different receptive fields and frequency ranges.

Limitations of vibrotactile sensation: Broad localization of the sensation, superficial feedback and thus the strength of the vibration may be perceived differently based on the area of skin in contact with mounting pressure.

### Kinesthetic

Very accurate receptors in muscles, joint and skin. All about movement and force.

Passive Kinesthetic (Force feedback): Perception of resistance or force, it requires human motion/input. Examples are surgical simulators or controllers.

Limitations to passive kinesthetic:

- Hard to design
- Often cumbersome
- User needs to provide input
- Limited part of how we perceive the world

## Active Kinesthetic

Focuses on the sense of body movement and position. Relevant in motion simulators, exoskeletons and teleoperation systems.

Limitations to passive kinesthetic:

- Hard to design
- Often cumbersome
- Expensive
- Limited part of how we perceive world

## Current Limitations of Haptics

The chain is: System state triggers an actuator, which in turn is perceived by a human.

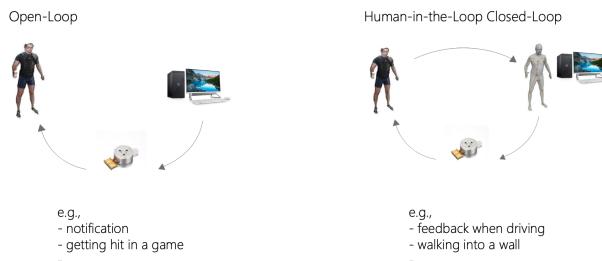
Kinetics are currently not common in user electronics.

- Kinetics are currently not common in user electronics.
- Human state is not taken into account
- Current systems only react to system states
- We are limited to vibrotactile feedback
- This leads to underperforming and underwhelming feedback

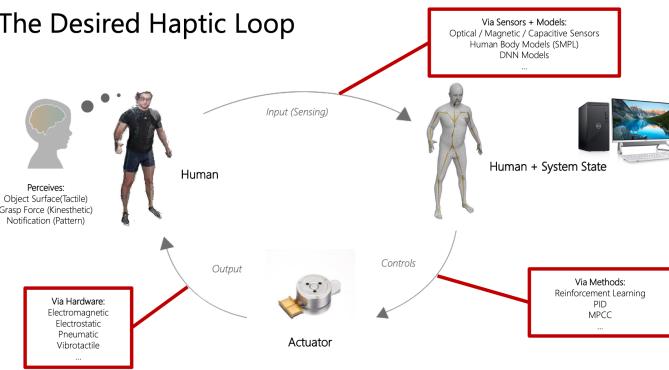
## How to overcome these limitations?

- Enable sensing of human state
- Use human state to control the device intelligently
- Using Closed vs open loop
- Body pose as a first step for truly intelligent haptic feedback systems

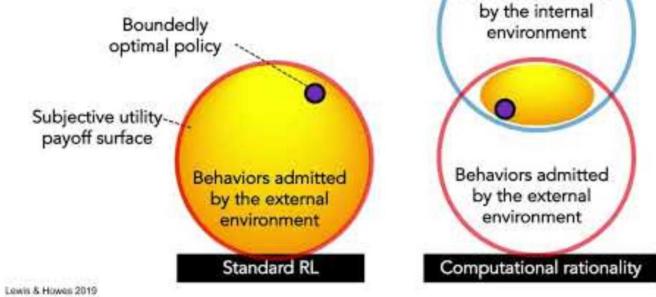
Add control:



## The Desired Haptic Loop



## Policy estimation view



Interaction is a sequential decision-making process

**Optimal Policy**

*Reinforcement Learning*

*Difference to other ML paradigms*

*Markov Decision Process*

*Optimal action given a state*

*Value Function*

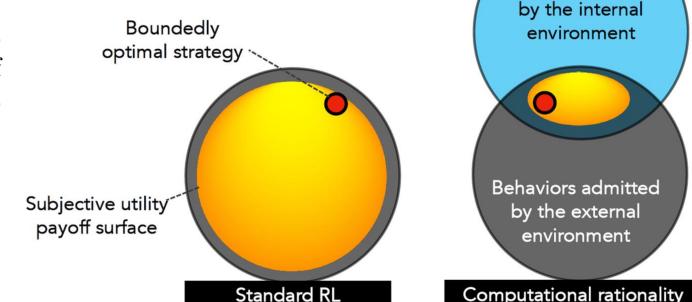
*On Rewards*

**Bounded Rationality**

*Comparison with Standard RL*

*Internal vs External Environment*

## Bounded optimality



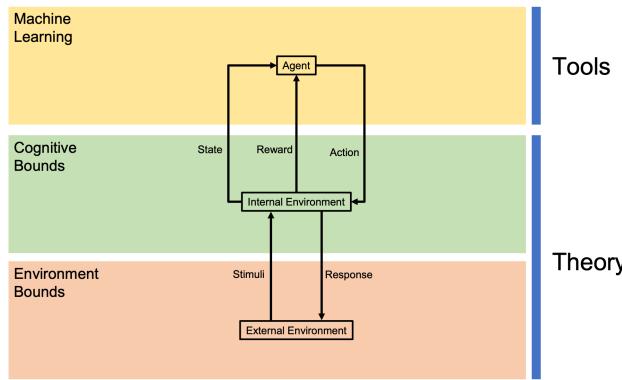
It has been found that more complex shapes benefit most from feedback. And users are still limited by the speed of the system. But overall drawings are more accurate than way.

## 12 Computational Rationality

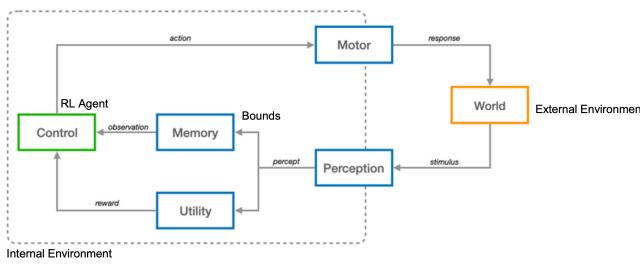
### Why User Models

#### Limitations to MHP

#### Complexities of real-world tasks



The cognitive architecture



## Key cognitive capacities in HCI

*General props of Human Cognition*

1. Cognition is goal oriented
2. Cognition Adapts
3. Cognition Learns
4. Cognition computes based on internal representations
5. Cognition is limited & costs energy

*Perception*

*Elementary perceptual Tasks*

## Gaze-based Interaction

*Comparison with Cognitive Architectures*

Cognitive Architectures	Computational Rationality
An information processor	An agent
Manually specified rule set	Policy is optimized (e.g., RL)
Bounded by cognition	Bounded by cognition
Architecture	Decision-problem