Theories and Models for Human-Computer Interaction

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Outline

What is a theory? a model?

Perception, action

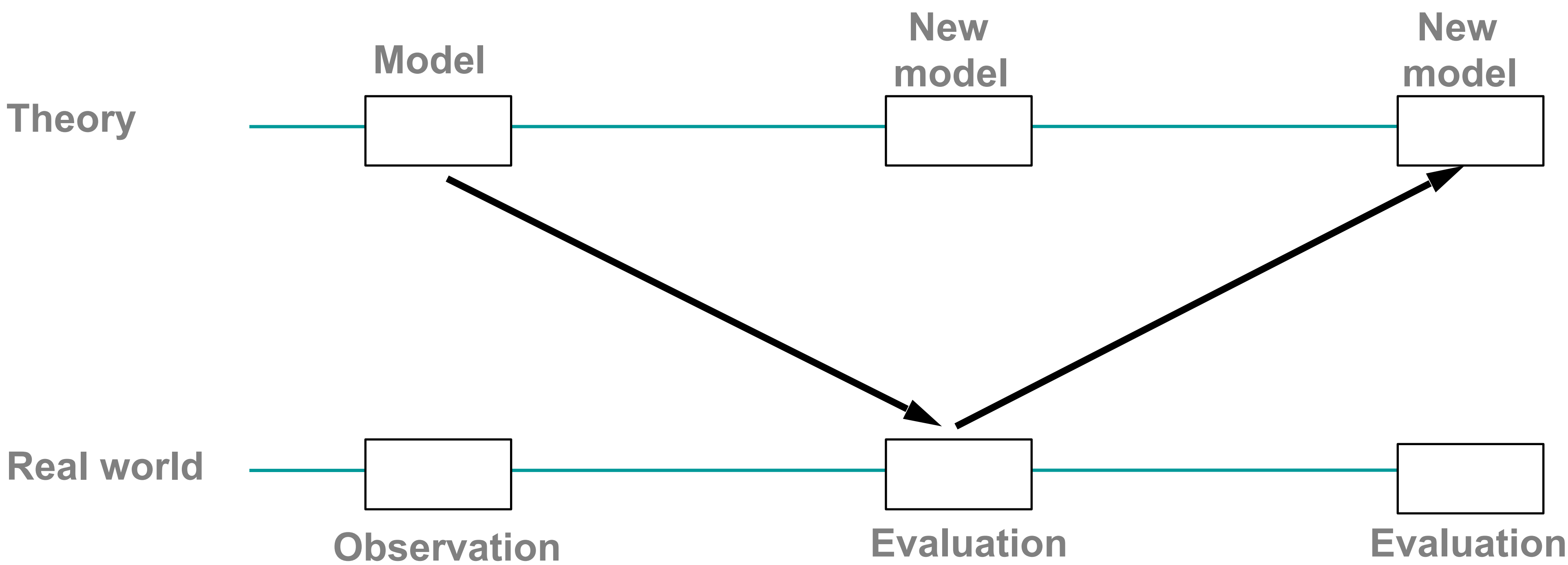
Cognition, behavior

Interaction

Software architectures

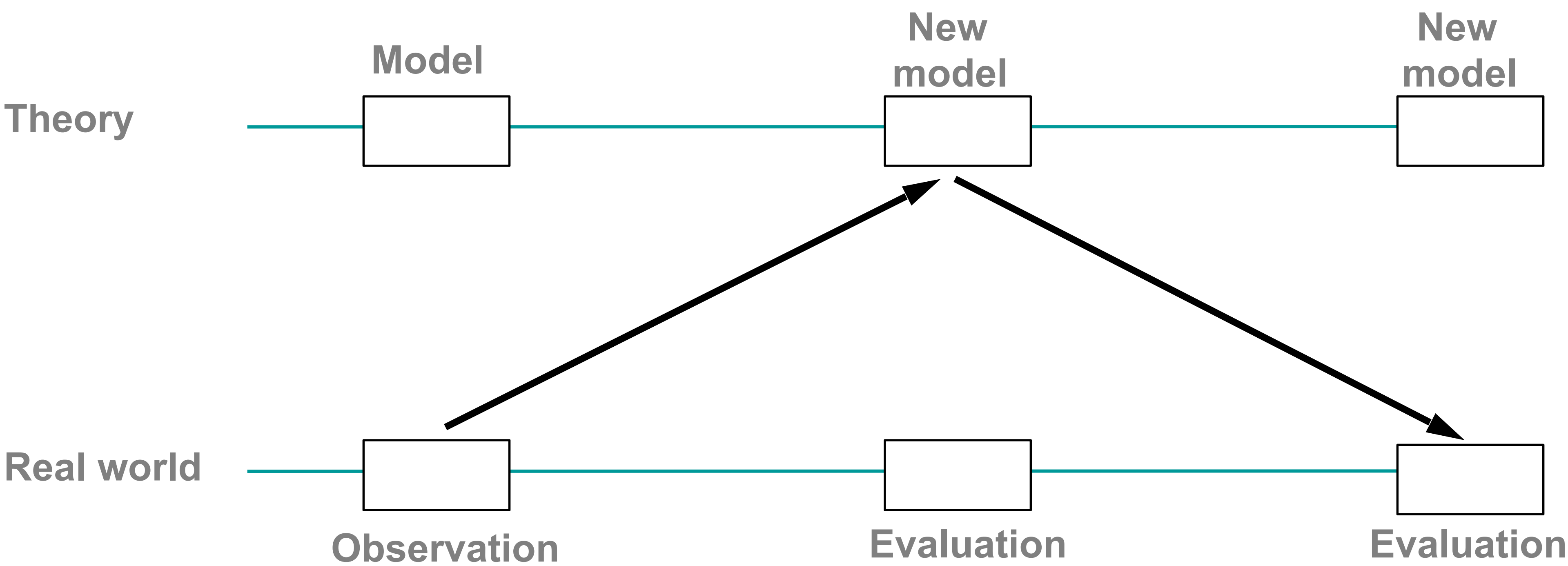
HCI as a scientific discipline

Natural sciences



HCI as a scientific discipline

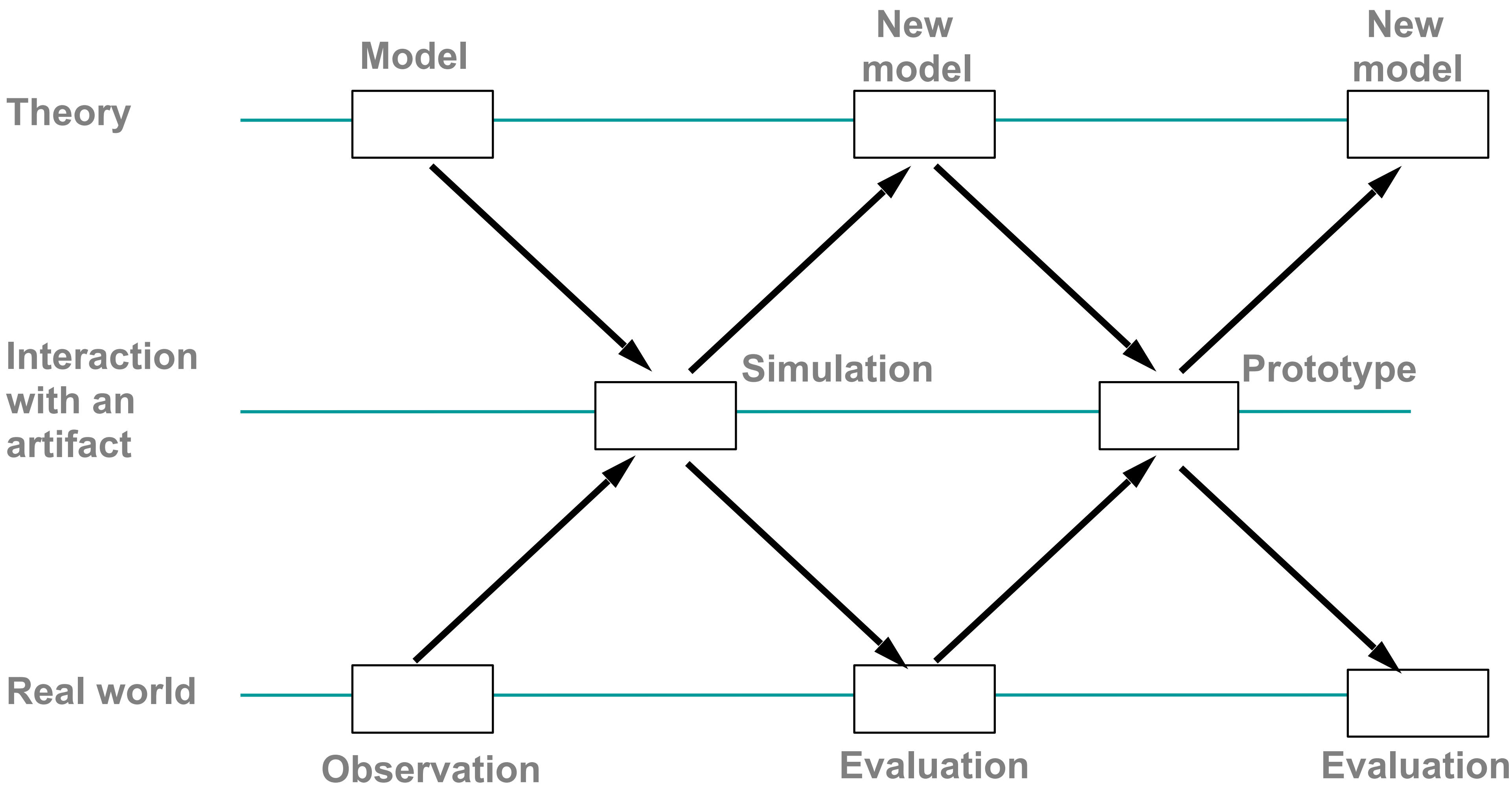
Natural sciences



HCI as a scientific discipline

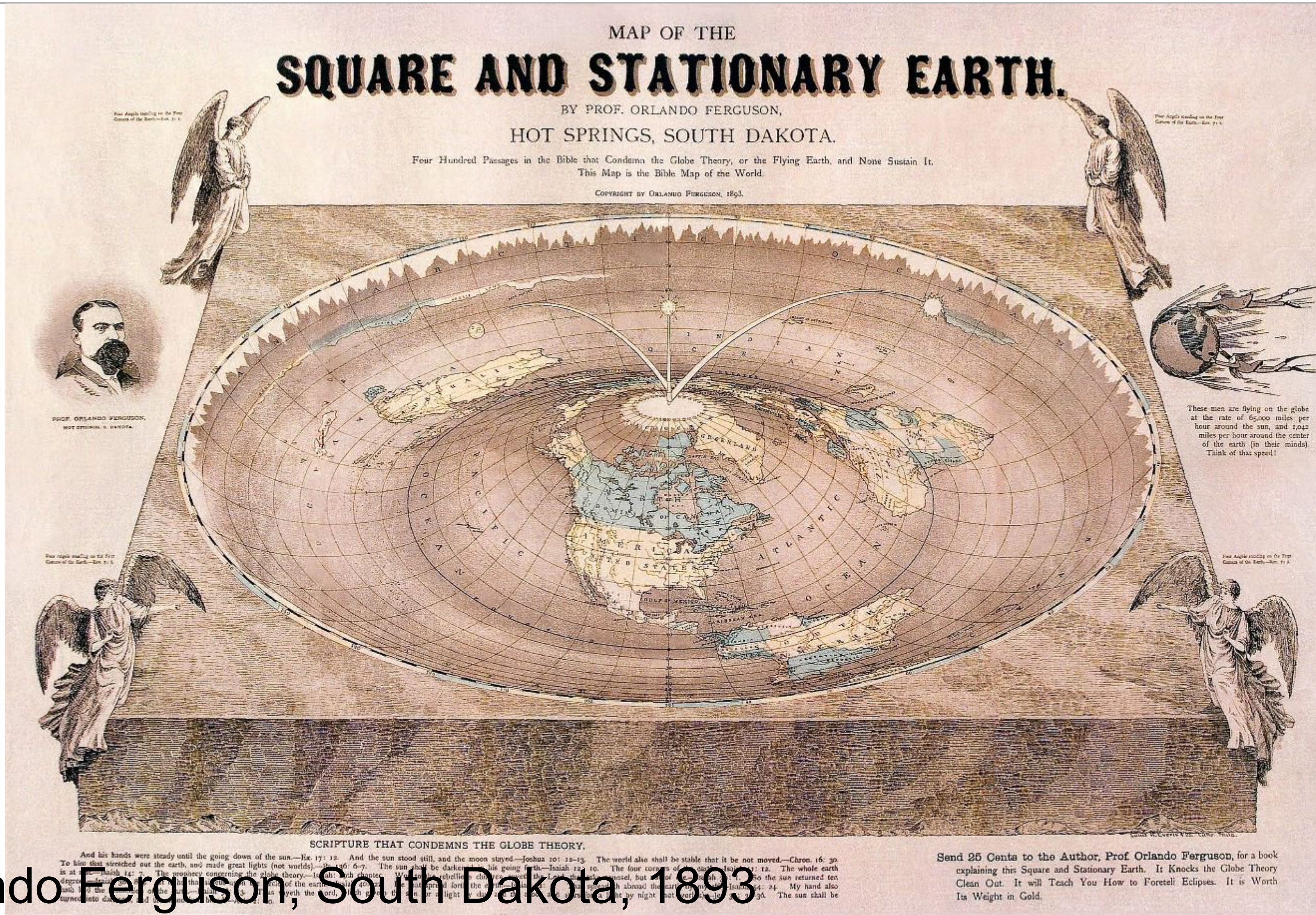
Mackay & Fayard

Sciences of the artificial



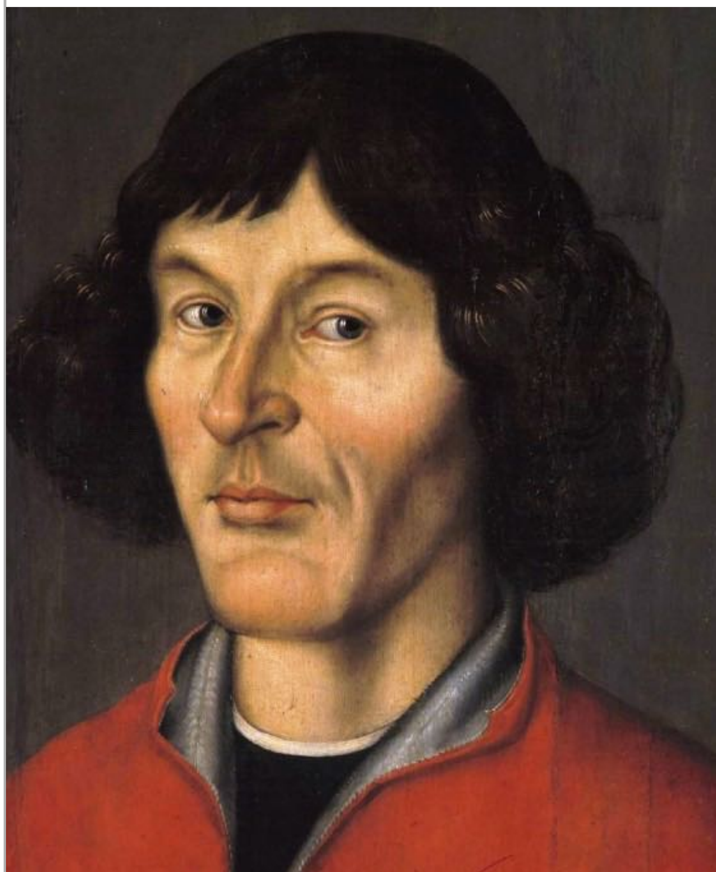
Models and theories: astronomy

Models and theories: astronomy



Orlando Ferguson, South Dakota, 1893

Models and theories: astronomy

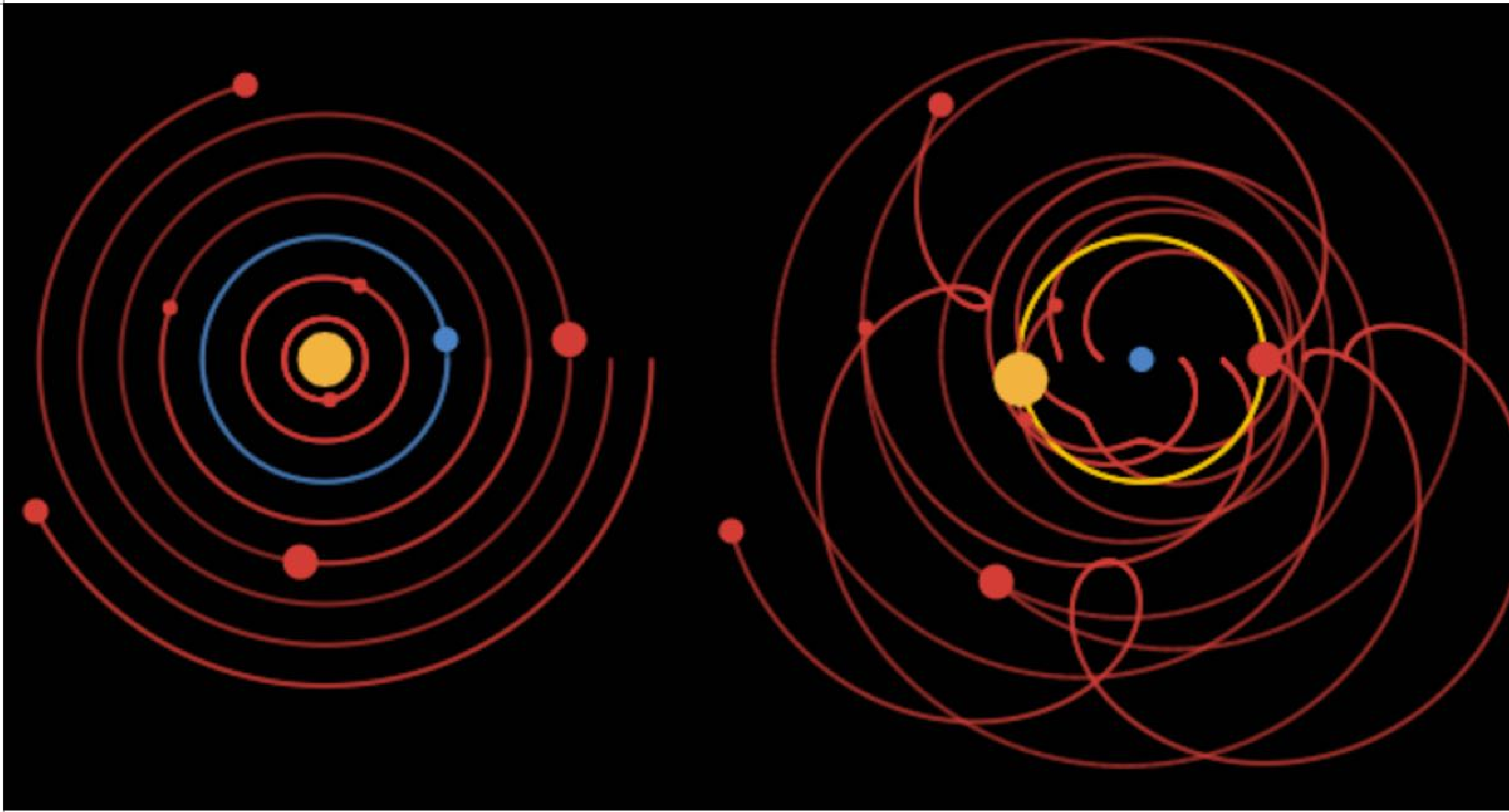


Copernicus (1473-1543)

Kepler (1571-1630)

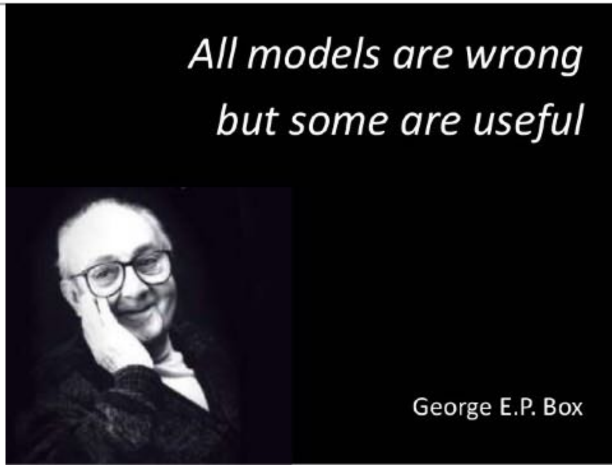
Galileo (1564-1642)

Models and theories: astronomy



Heliocentrism Geocentrism

What is a model?



Model = simplification of reality

- Goal: to be useful!
- Abstraction of reality: omit non-relevant details
- Conflict between precision and generality: choose the level of abstraction

Power of a model

- Descriptive: ability to represent (aspects of) a phenomenon
- Predictive: ability to anticipate behavior
- Generative : ability to imagine new solutions to a problem

Notation = description language

- Not a model
- Informal, incomplete, inconsistant
- Example : UAN (User Action Notation)

What is a theory?

Theory = (attempt to) explain reality

- Often based on a model
- Validity not only of the predictions of the model, but also of the model itself

Falsifiability [Popper]

- A scientific theory must be disprovable through experiments
- A falsified theory can be refined into a “better” theory
  - Example : Newton -> Einstein
    Relativity refines (and includes) classical mechanics

Empirical law = observation of a regularity, without explanation

- Not a theory

Psychological theories of human behavior

Biological [Darwin]
- Biological causes of behavior and emotion

Psychodynamic [Freud]
- The role of the unconscious

Behavioral [Watson, Skinner]
- Stimulus-response

Cognitive [Neisser, Chomsky, Miller, …]
- Internal states of the brain

Humanistic [Rogers, Maslow]
- Concept of the self, subjective experience

Psychological models of human behavior

Biological [Darwin]
- Genetics, hormones

Psychodynamic [Freud]
- The id, ego and superego

Behavioral [Watson, Skinner]
- Positive or negative reinforcement, Operant conditioning

Cognitive [Neisser, Chomsky, Miller, …]
- Information processing

Humanistic [Rogers, Maslow]
- Hierarchy of needs, Individual desire to fulfill one’s potential

Perception and action

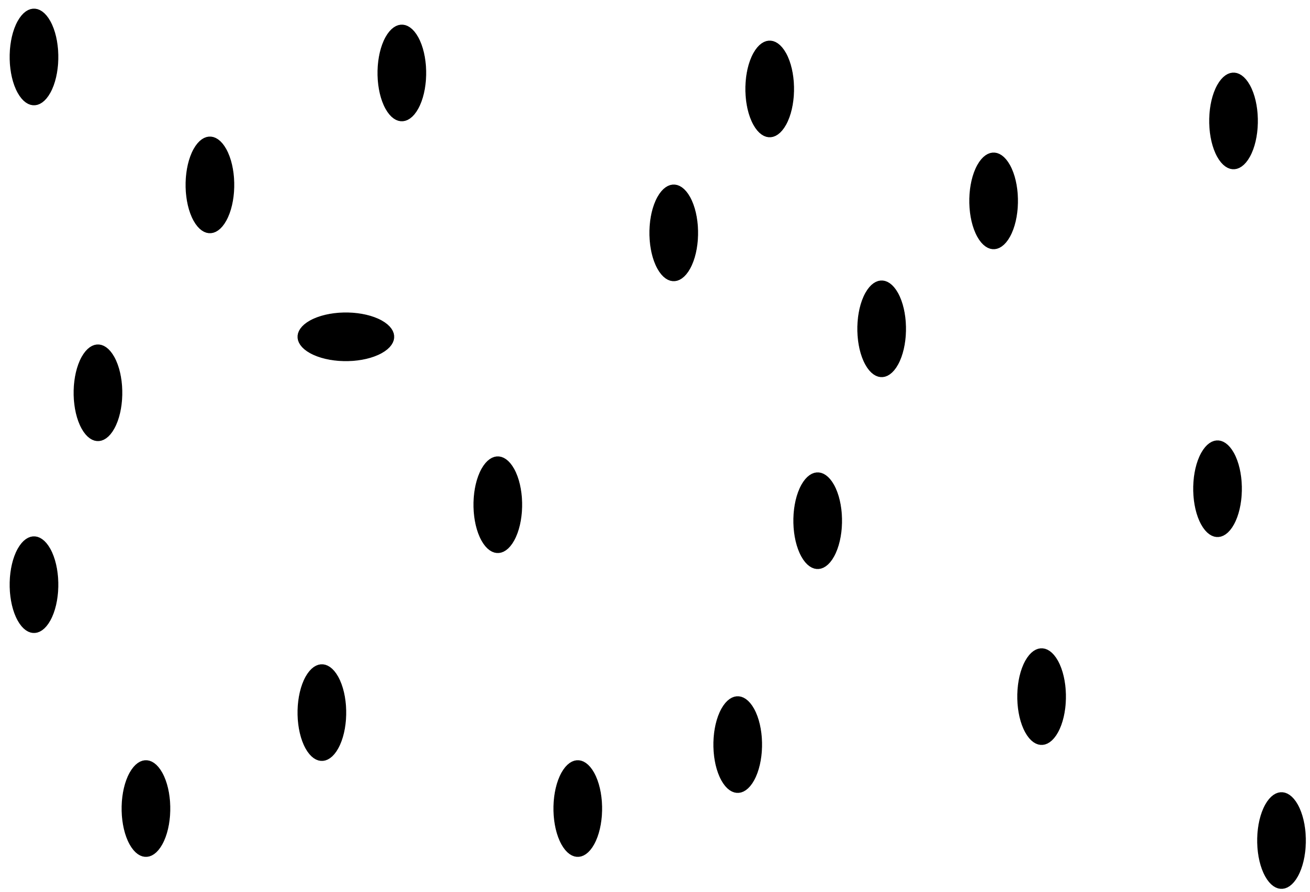
Pre-attentive perception [Triesman]

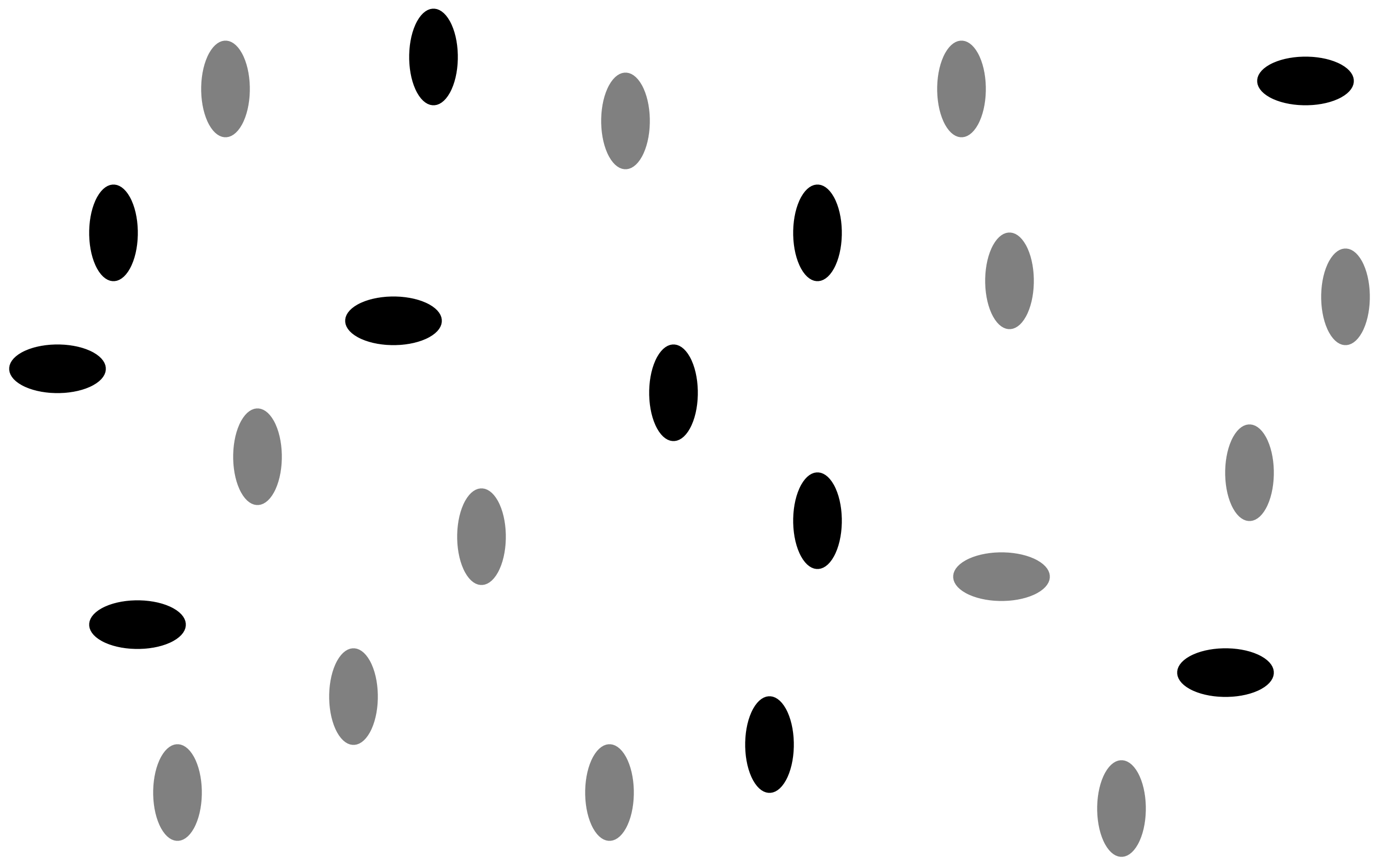
Ecological theory of perception [Gibson]

Hick's law

Fitts' law

Kinematic chain theory [Guiard]



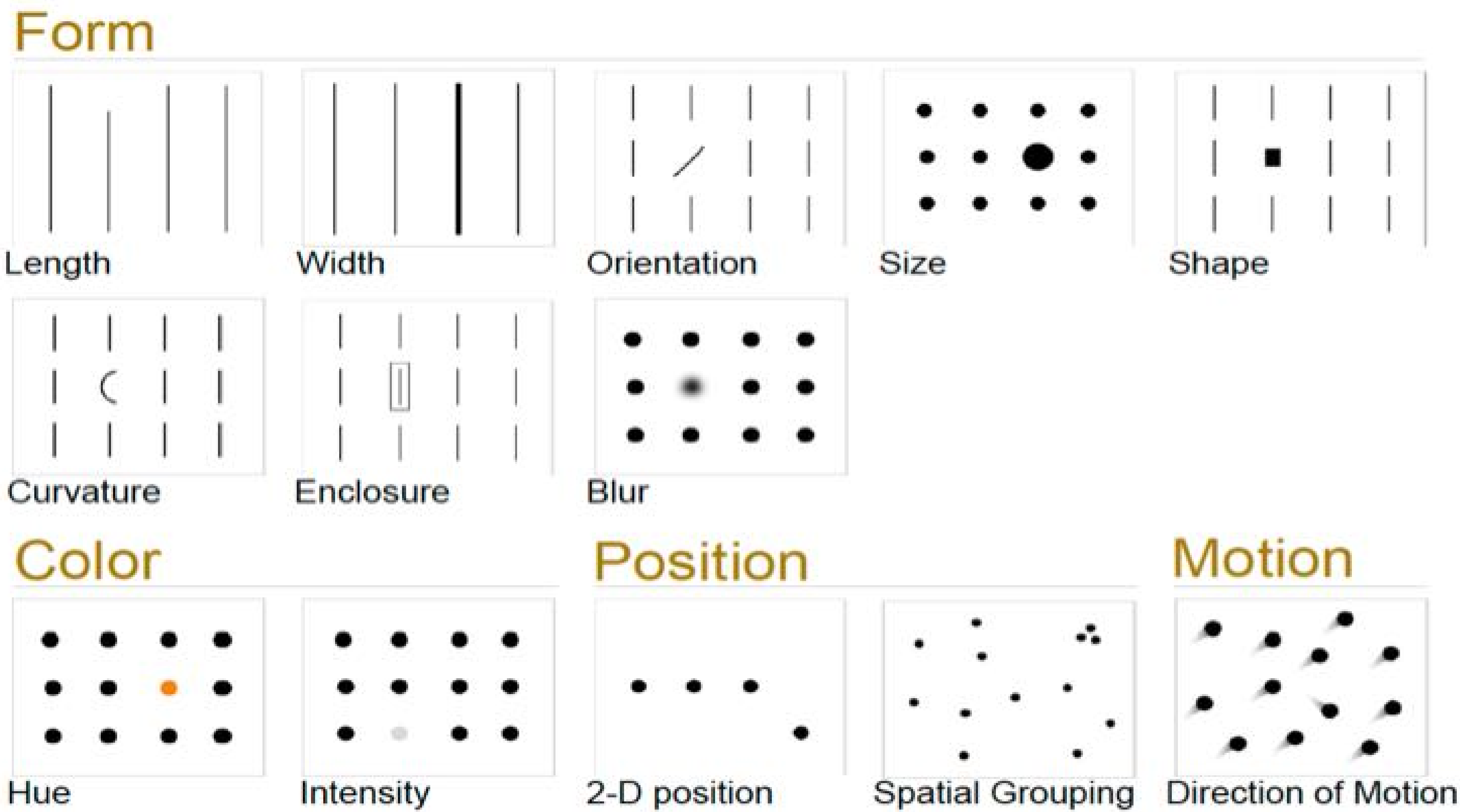


Pre-attentive perception

Observation :

- Humans can recognize some visual features very rapidly:
- Line orientation, blobs, length, thickness, size, curvature, cardinality, endings, intersections, inclusion, hue, blinking, movement direction, depth, direction of light source…

Pre-attentive attributes



Source: BrightMetrics, Using Color in Data Visualization

Pre-attentive perception

Observation :

- Humans can recognize some visual features very rapidly:
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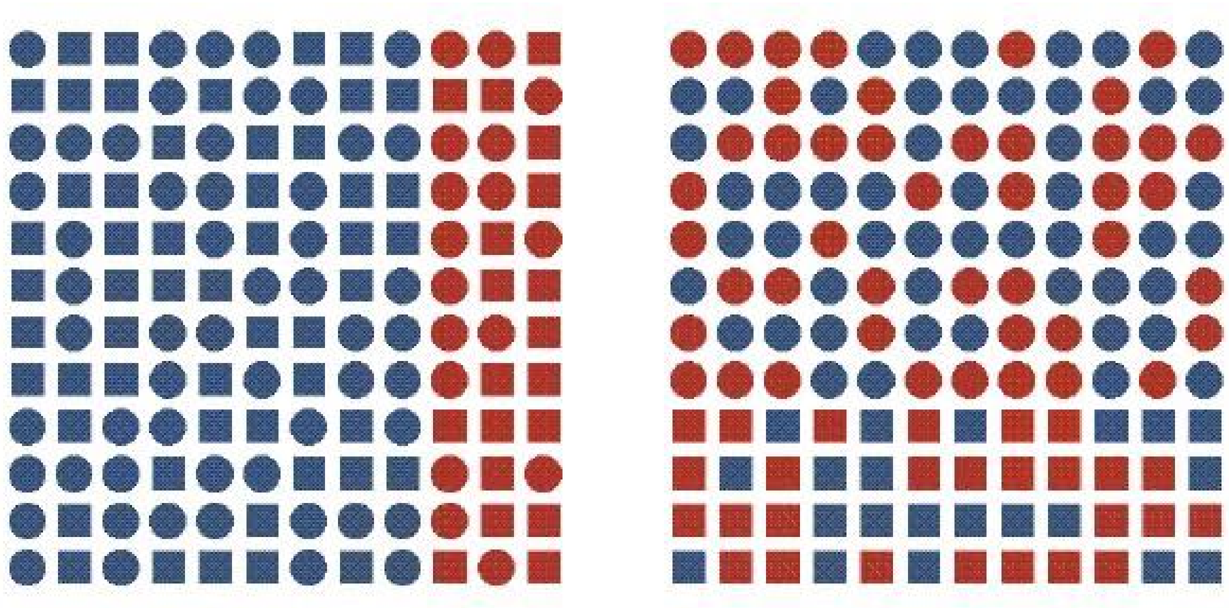
- There are interferences when combining several such changes



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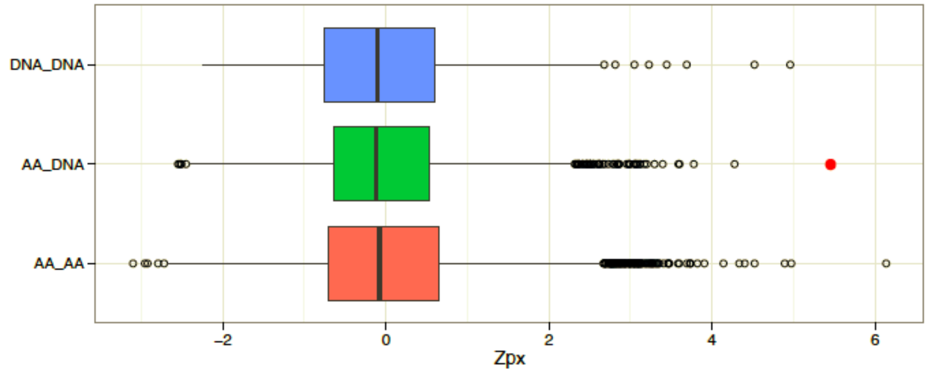
Theory : pre-attentive perception (Triesman, 1985)

- Parallel handling at the level of visual perception
- Information that is not perceived pre-attentively must be handled sequentially
- Links with Gestalt theory

Pre-attentive perception: application

Information visualization:

Use pre-attentive attributes to emphasize outliers

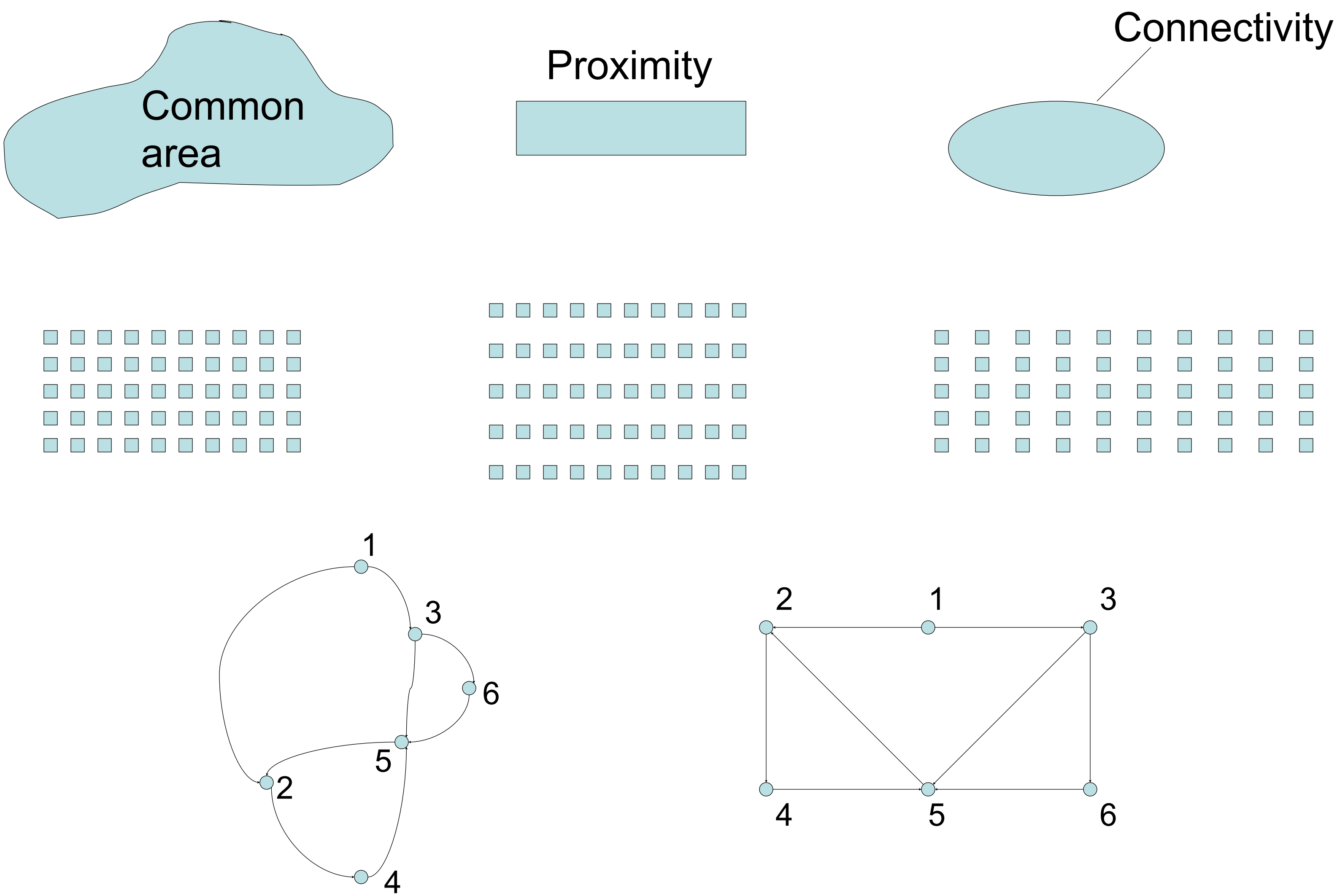


User Interface design:

Use color or other pre-attentive attribute to draw attention

27107462144654207079014738109743897010971
45929078059772098775972655665110049836645
25747072354745666142018774072849875310665
43907097349266847858715819048630901889074

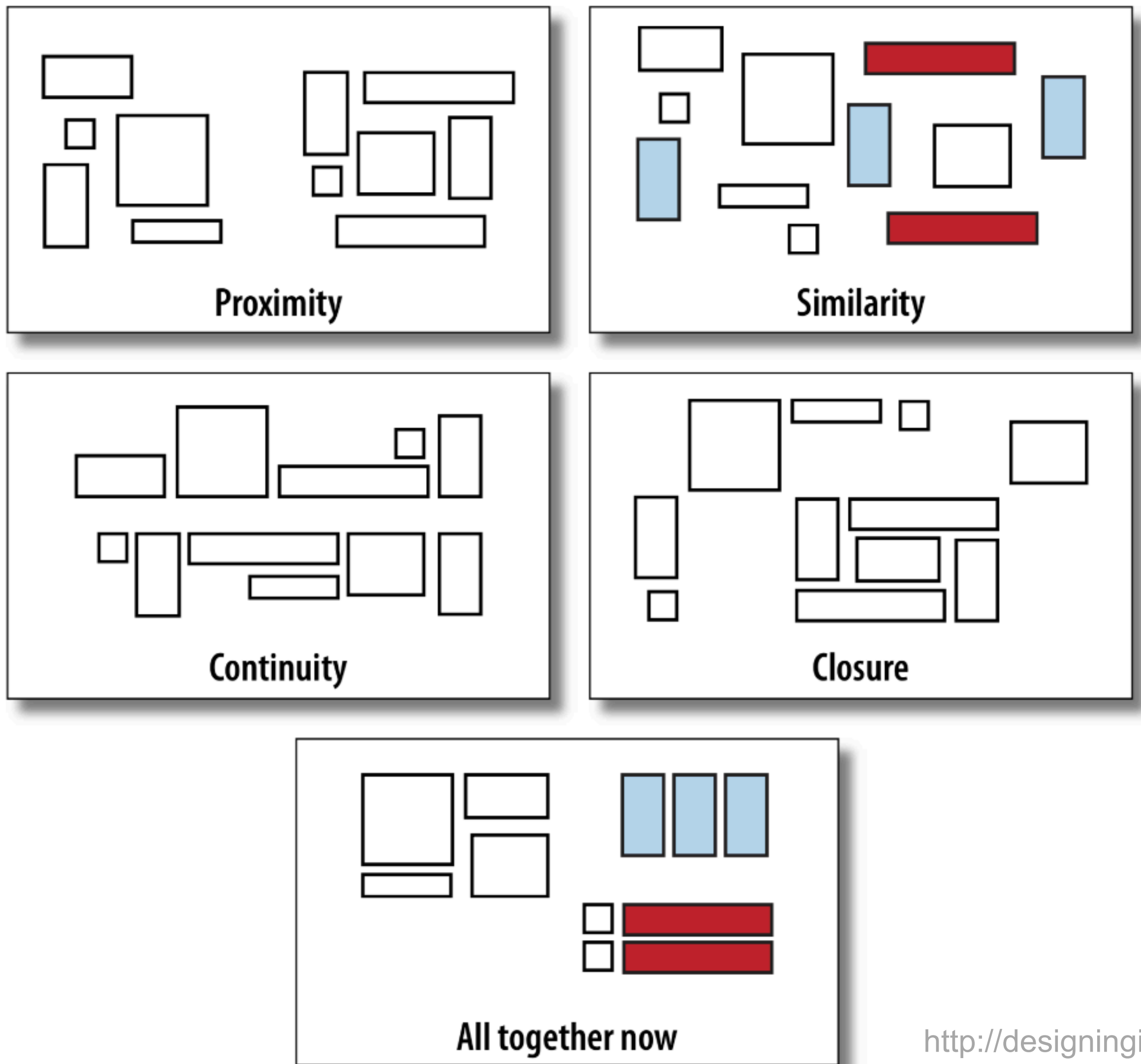
Principles of Gestalt perception



Principles of Gestalt perception: application

http://designinginterfaces.com/firstedition

Principles of Gestalt perception: application



http://designinginterfaces.com/firstedition

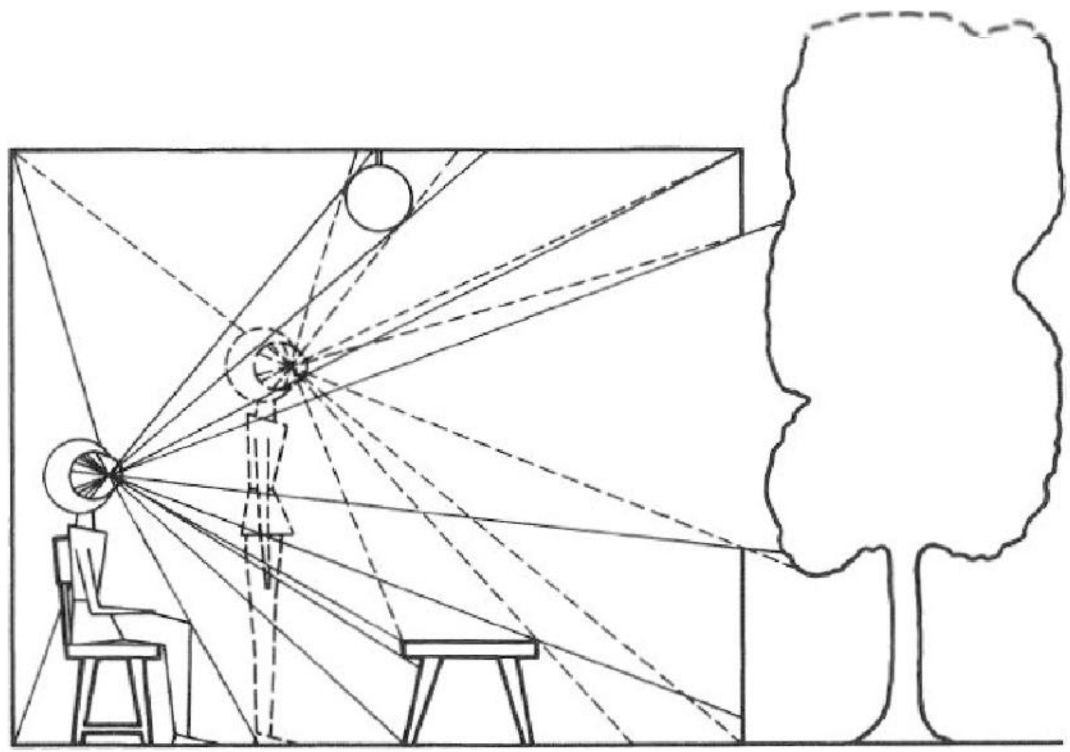
Ecological Theory of Perception

Fundamental hypotheses:

- Co-evolution between organism and its environment
- Behavioral pre-adaptation
- “Elegant” (and parsimonious) perceptual processes

Ecological Theory of Perception

Ecological optics
- Information is in the optical array

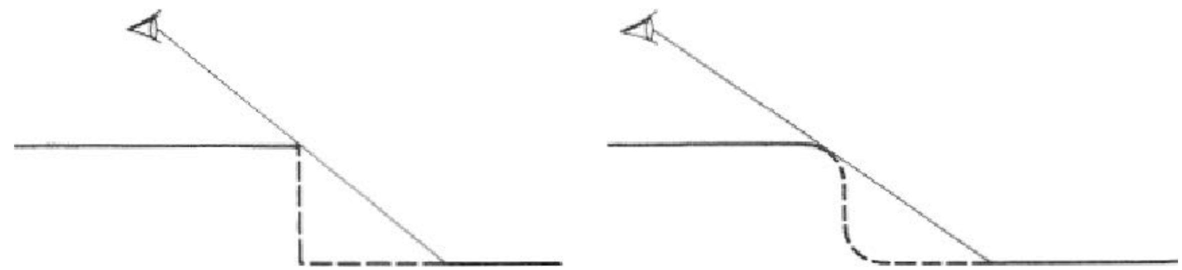


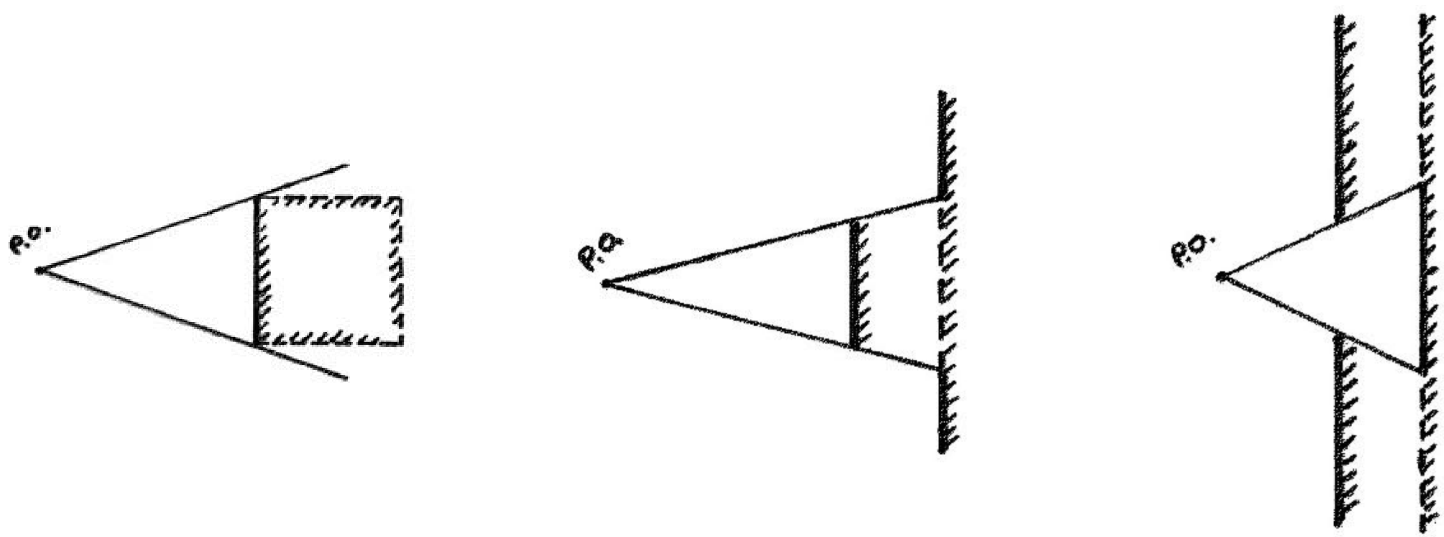
James J. Gibson

Ecological Theory of Perception

Ecological optics

- Information is in the optical array
- An occluding edge reveals depth information



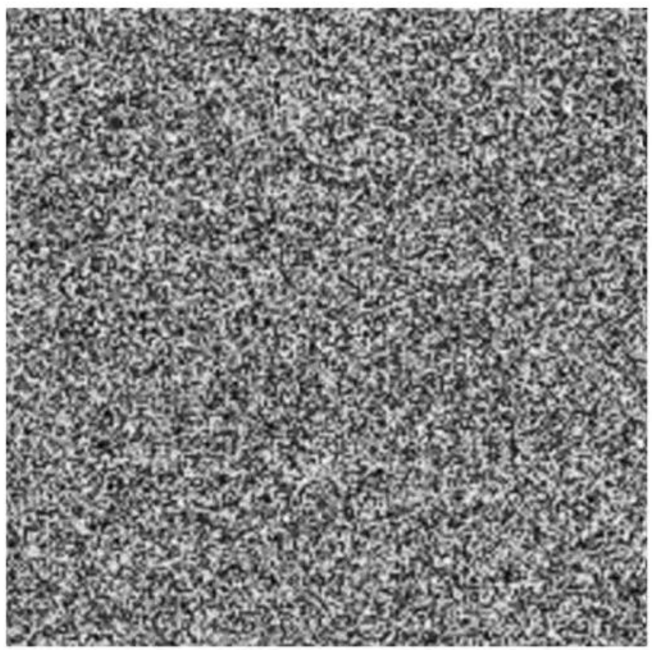


James J. Gibson

Ecological Theory of Perception

Ecological optics

- Information is in the optical array
- An occluding edge reveals depth information
- Information is in the optical flow

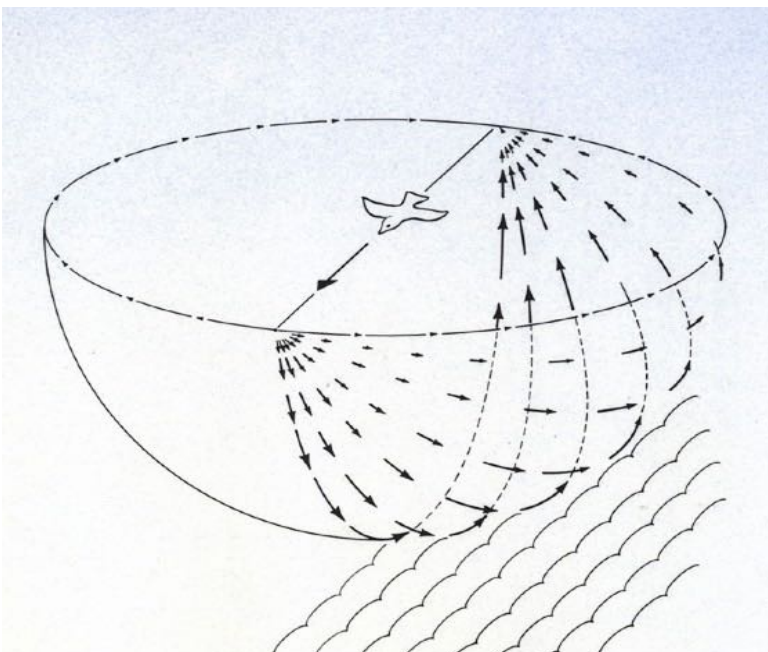


Ecological Theory of Perception

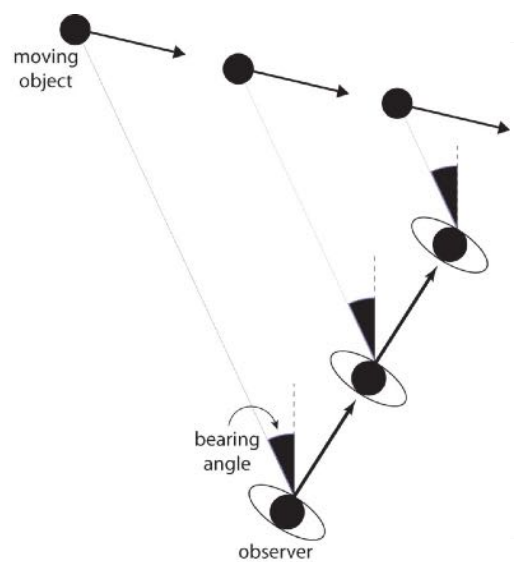
Ecological optics

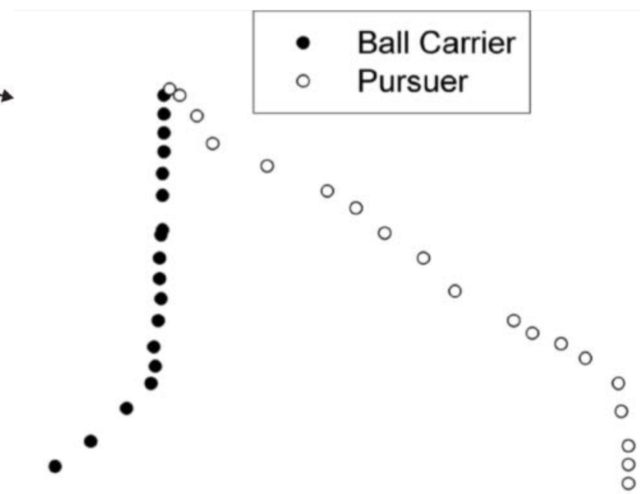
- Information is in the optical array
- An occluding edge reveals depth information
- Information is in the optical flow
- The organism is equipped to extract invariants

- When moving, the only fixed point indicates the direction of motion



- To catch a ball, keep a constant angle between the ball and your direction of motion





Ecological Theory of Perception

Ecological optics

- Information is in the optical array
- An occluding edge reveals depth information
- Information is in the optical flow
- The organism is equipped to extract invariants

Relativity of the environment

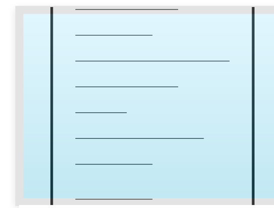
- Action-perception coupling
  - One must move to perceive, and perceive to move
- Perception of affordances
  - Capabilities of the environment for actions

James J. Gibson

Ecological Theory of Perception: applications

Ecological optics

- Overlapping windows
- Scrolling



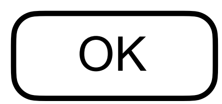
Action-perception coupling

- Perceive to act: Feedback
- Act to perceive: Feedforward

Affordances

- Objects should reveal their capabilities for action

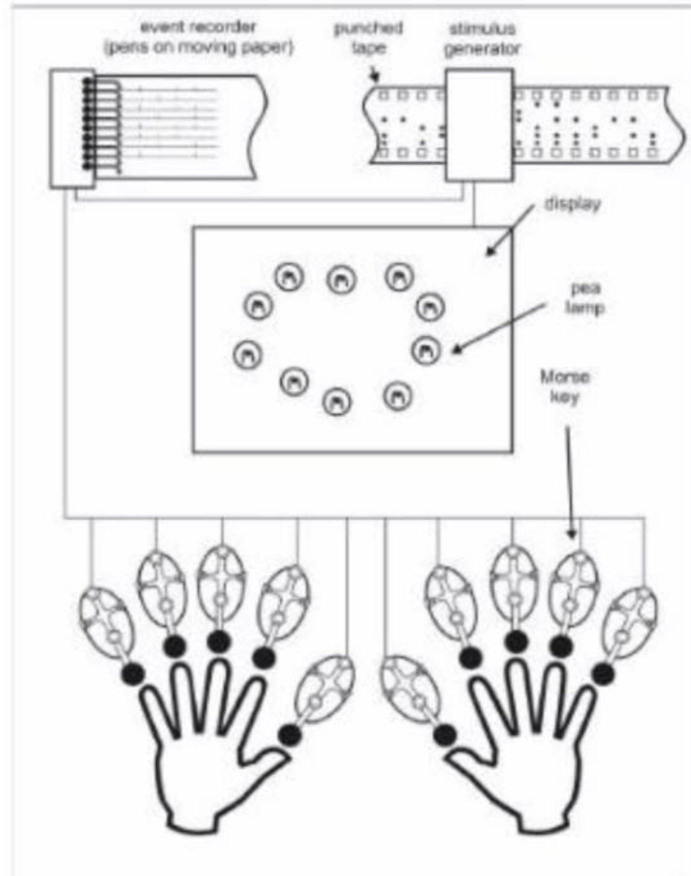
Add comment



Hick's law (1952) - also called Hick-Hyman law

Choice reaction time: time it takes to identify an item in a set

- $RT = a + b\,H$
  a & b are constants
  H is the entropy of the set of choices
- $H = \log_2(n)$ if all choices are equiprobable
  where n is the number of items
- $H = \Sigma p_i \log_2(1/p_i)$
  where p_i is probability of choice i



Was performed with highly trained participants
(Hick trained himself over 8,000 trials!)

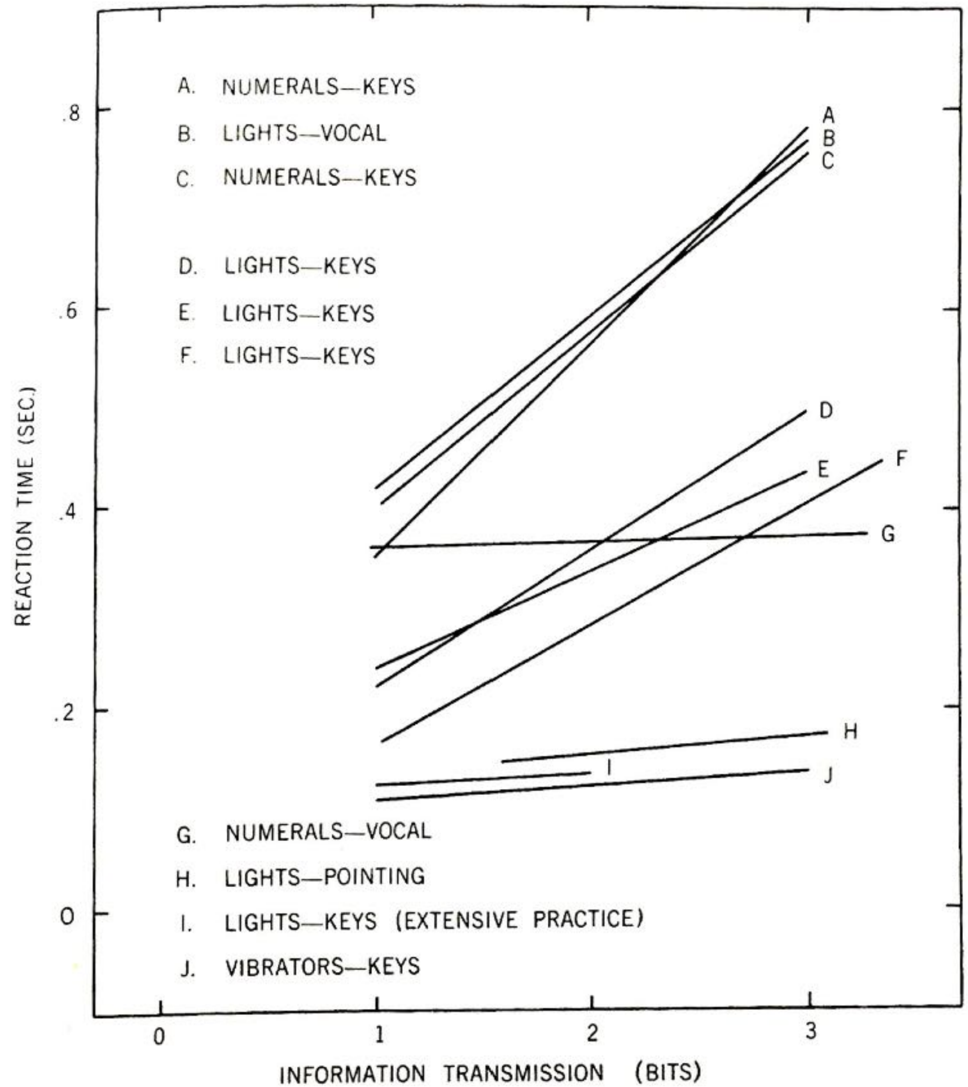
=> strong effect of learning

Hick's law (1952) - also called Hick-Hyman law

Effect of
stimulus-response compatibility

Performance higher if,
for example, the lights
are aligned with the key
to be pressed

Slope approaches 0 for
very high S-R compatibility,
e.g. spelling out a letter



Liu et al.

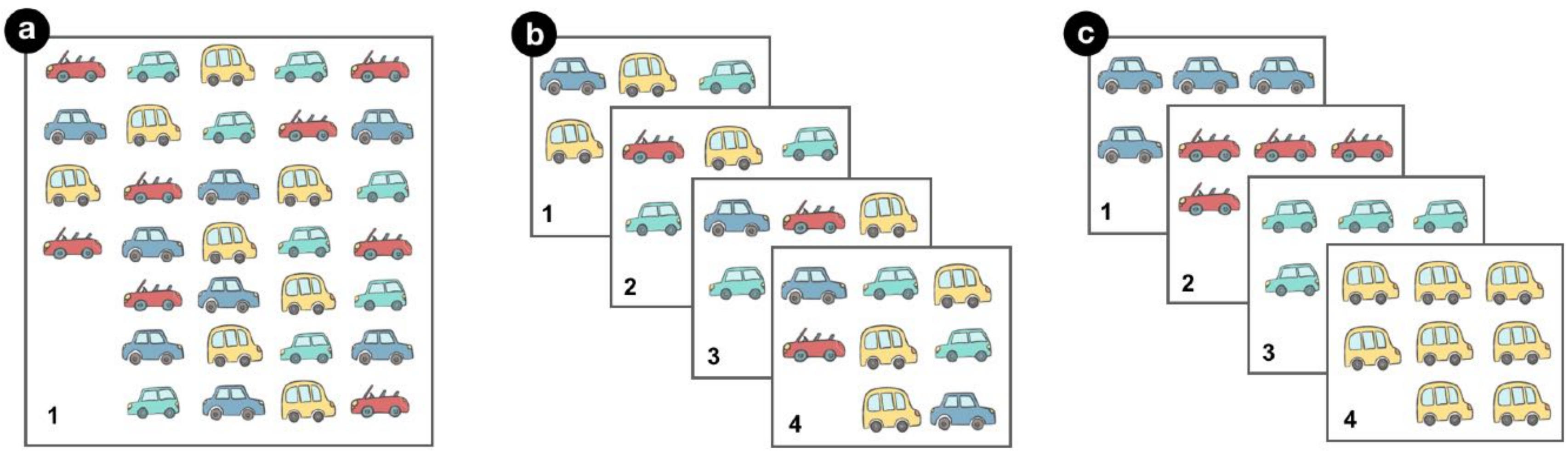
Hick’s law (1952) - applications (or not!)

Often used to justify the design of menu systems

- Reduce number of choices in each level
- Hierarchical menu better than flat menu

BUT in general not true!

- High S-R compatibility and over-learned tasks
  => almost constant reaction time
- Other factors at play: Hick’s law not relevant

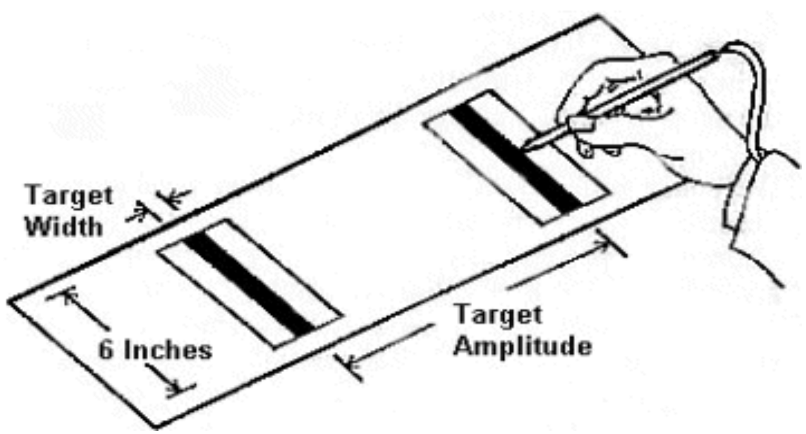


RT = a + 5b   RT = 2.5a + 7.5b   RT = 2a + 5b

Fitts' law (1954)

Fitts' law: time it takes to acquire a target

- $MT = a + b \log_2 (1 + D/W)$
  a & b are constants
  D = distance to target (amplitude)
  W = pointing tolerance (width of the target)
- Information-based theory of perception



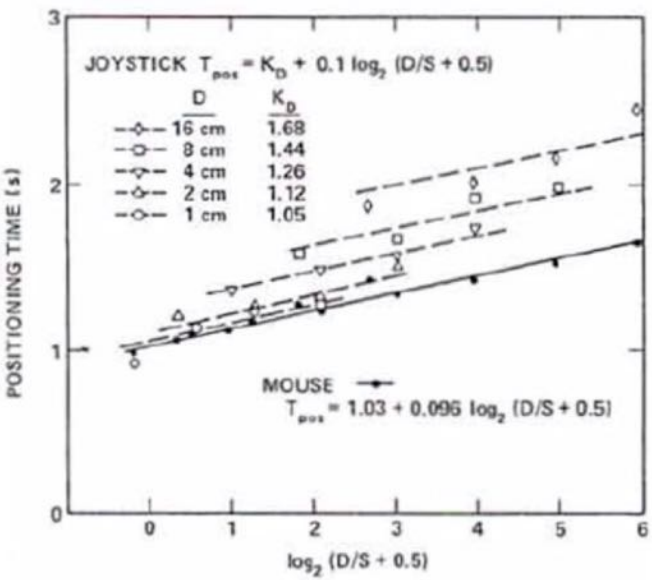
Empirical laws extracted from controlled observations

These laws are valid only in precise experimental settings

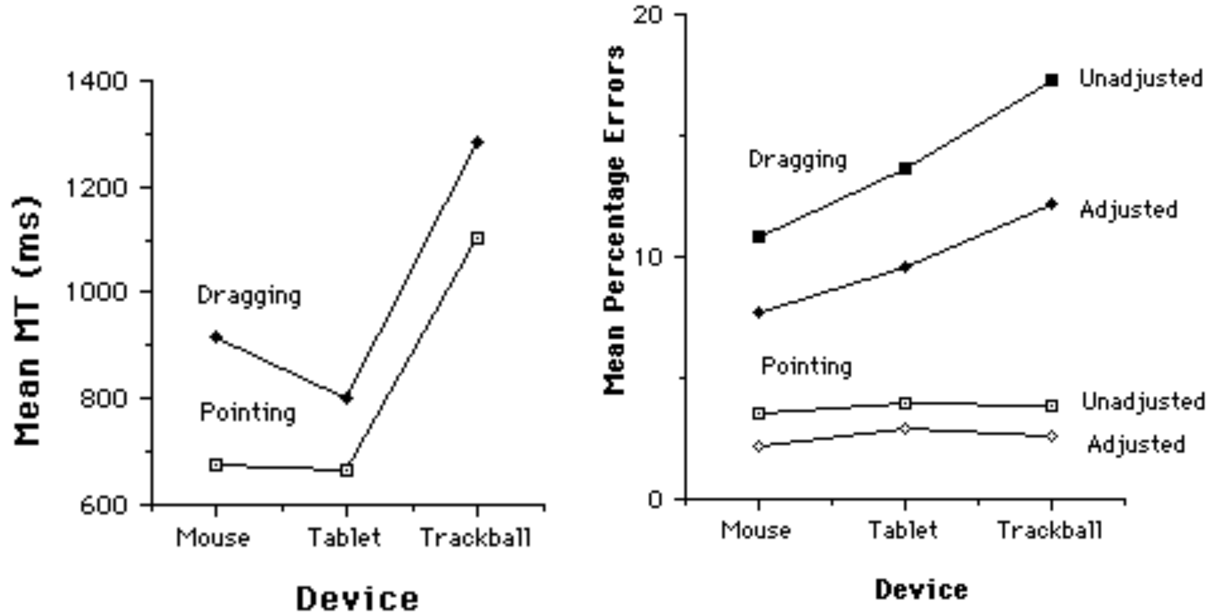
Fitts' law (1954) - applications

Assessing pointing devices

– Comparing a and b constants and error rates across devices



Card, English & Burr 1978



Mackenzie, Sellen & Buxton 1991

Creating and evaluating new pointing techniques

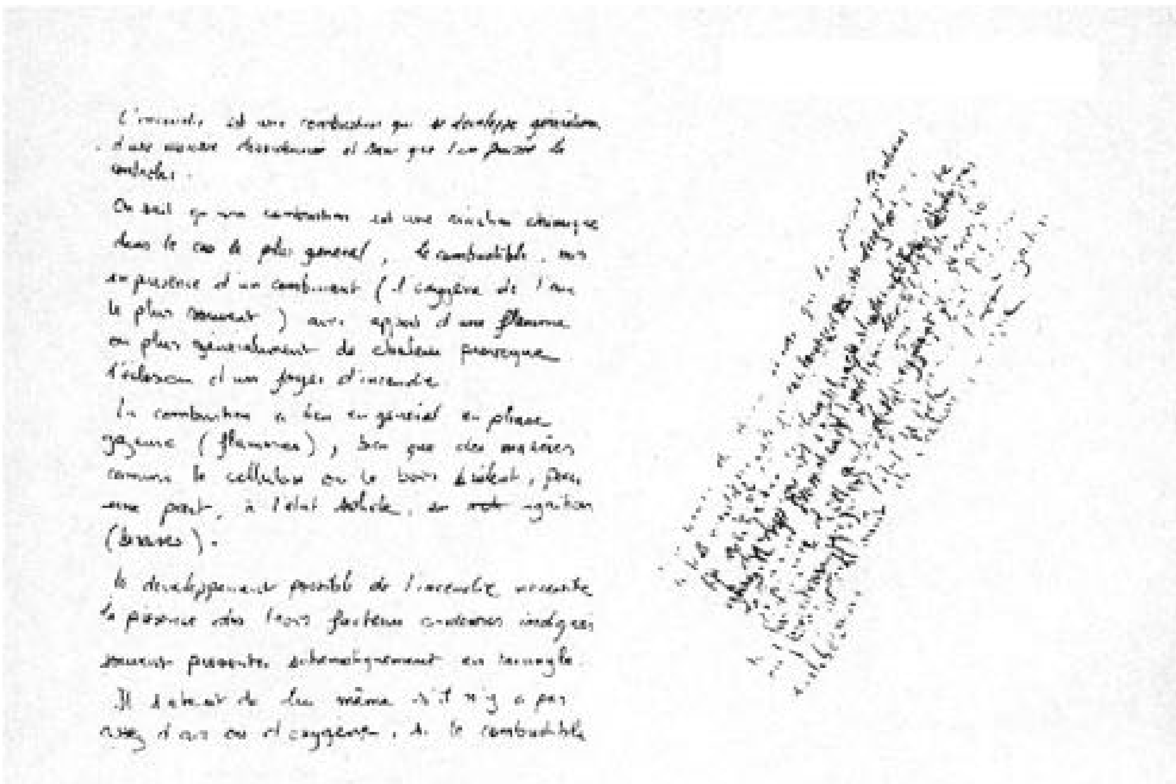
– Drag-n-pop, Semantic pointing, Bubble cursor, …

Yves Guiard

Kinematic chain theory

Laterality of motor control

- Classical psychology:
  “the left hand is a bad right hand”
- Observations of bimanual control:
  the two hands have different *roles*



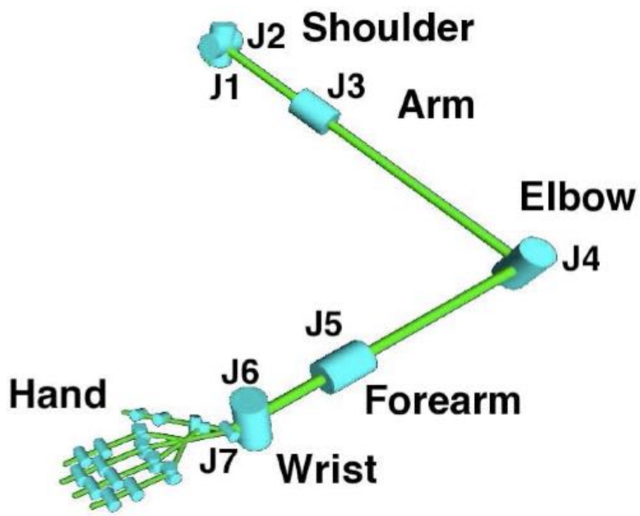
L'incendie est une combustion qui se développe généralement
d'une manière désordonnée et sans que l'on puisse la
contrôler.
On sait qu'une combustion est une réaction chimique
dans le cas le plus général, le combustible, mis
en présence d'un comburant (l'oxygène de l'air
le plus souvent) avec apport d'une flamme
ou plus généralement de chaleur provoque
l'éclosion d'un foyer d'incendie.
La combustion a lieu en général en phase
gazeuse (flammes), bien que des matières
comme la cellulose ou le bois [illegible], puis
une part, à l'état solide, en auto-ignition
(braises).
Le développement possible de l'incendie nécessite
la présence des trois facteurs ci-dessus indiqués,
souvent présentés schématiquement en triangle.
Il s'ensuit de lui-même s'il n'y a pas
assez d'air ou d'oxygène, si le combustible

Yves Guiard

Kinematic chain theory

Kinematic chain:

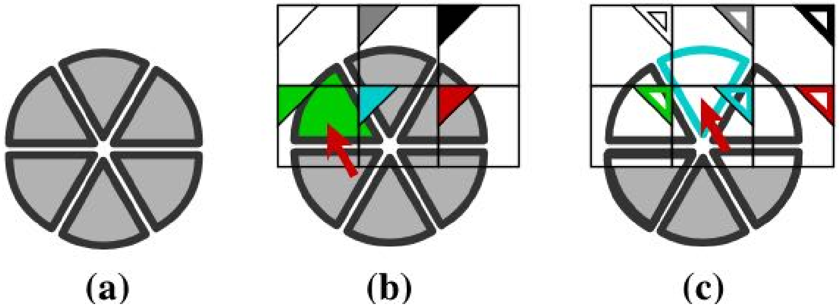
- Non-dominant hand: distal control
  - Acts first
  - Establishes the frame of reference (context) for the dominant hand
  - Movements do not need to be precise
- Dominant hand: proximal control
  - Acts after the non-dominant hand, within the frame of reference it establishes
  - Precise movements



Kinematic chain theory: applications

Bimanual interaction

- First study by Myers & Buxton (1986)
  Selection and navigation task
- Bier et al. (1993)
  Toolglasses and Magic Lenses
- Fitzmaurice, Ishii & Buxton (1995)
  Graspable interfaces



Toolglasses and Magic Lenses,
Bier et al., SIGGRAPH 1993

Graspable interfaces

Yves Guiard

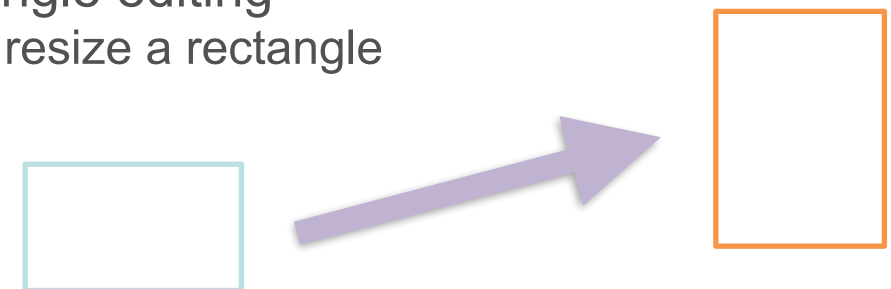
Kinematic chain theory

Falsification:

- Some tasks are more efficient when the hands have symmetric roles

Example: Rectangle editing

- Move and resize a rectangle



- Asymmetric assignment:
  - non-dominant hand moves the rectangle
  - dominant hand adjusts the size
- Symmetric assignment:
  - one hand moves one corner, the other hand the other corner
- Symmetric assignment more efficient

Cognition and behavior

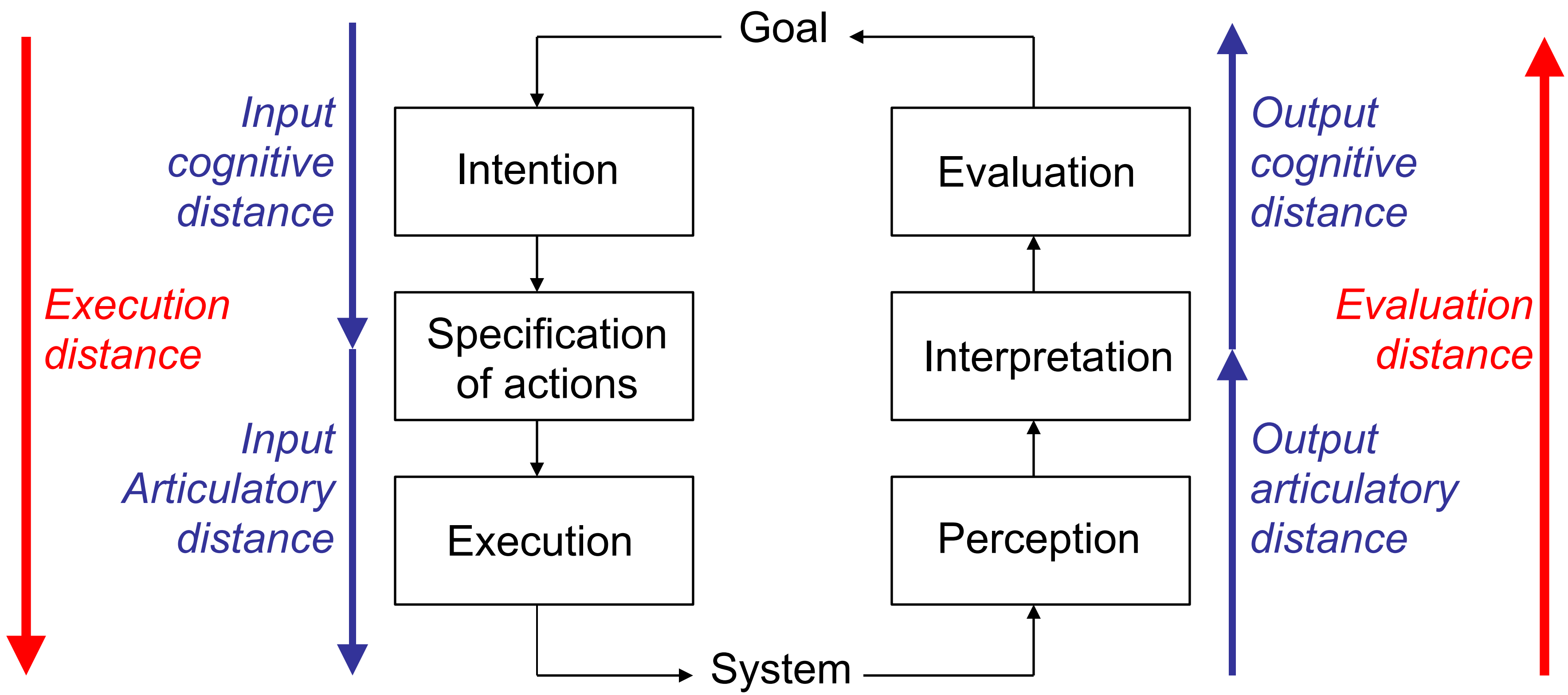
Seven stages of action [Norman]

Situated action [Suchman]

Activity theory [Vigotsky, Bødker]

Cognitive dimensions [Green]

Seven stages of action



Seven stages of action - applications

Analyze a design to assess the *gulf of execution:*

Input cognitive distance: what can I do?

=> make functionalities visible

Input articulatory distance: how can I do it?

=> feedforward, good mapping

Analyze a design to assess the *gulf of execution:*

Output articulatory distance: what happened?

=> feedback & response

Output cognitive distance: what does it mean?

=> good mapping, metaphor

Situated action

Classical cognitivist approach:

- Cartesian model where all actions are planned and human action is explained by cognitive processes
- Examples : action theory, task analysis, mental models

Ethnomethodological approach:

- Detailed analysis of work practices in order to determine the causal chains implied by the observed actions

Situated action:

- Human action takes place in a complex context that creates constraints and dependencies and affects the actions being undertaken
- If there is a plan, at best it is used as a guide
- Action adjusts to the context at hand and at the same time modifies it

Situated action: Ethnography and the PARC copier

Situated action - applications

Study your users!

Design for actual use in context,
not theoretical use

Observe breakdowns: When things don't go as expected

=> redesign to reduce causes of errors

Observe workarounds: How users find alternative ways

=> flexibility provides more opportunities

Observe user innovations: How they appropriate technology

=> unusual use becomes a feature

Vigotsky - Leontiev - Bødker

Activity theory

Vigotsky: analysis of human activity

– Subject-object relationship is mediated by tools (technical instruments) or signs (psychological instruments)

Leontiev : emphasis on the role of the community

– Rules and rituals, division of labor

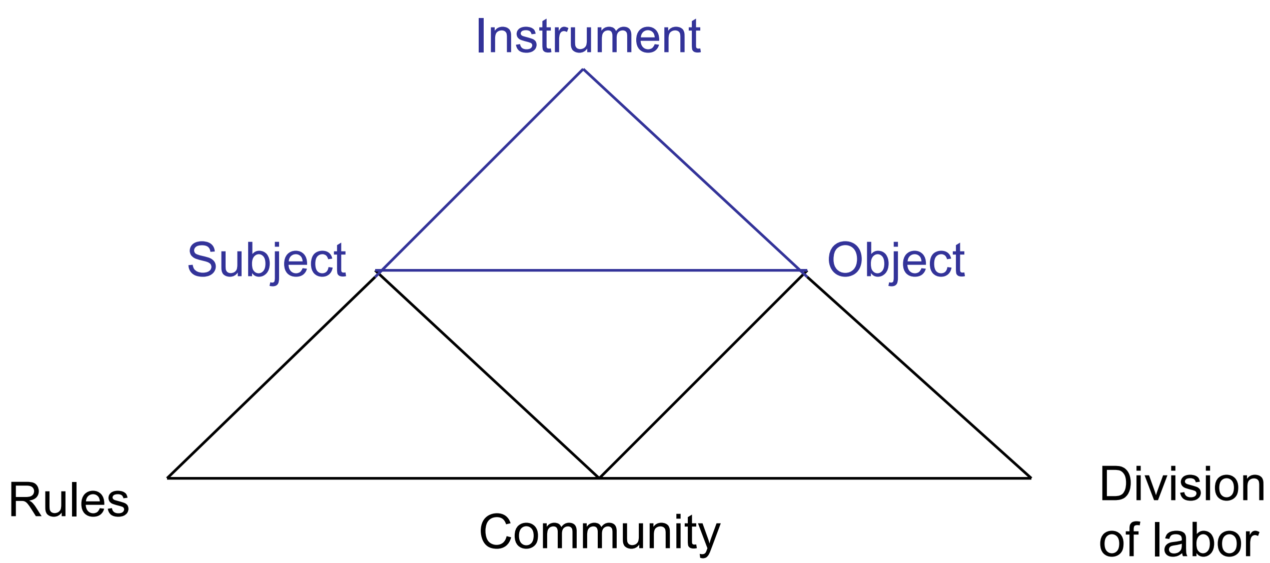
3 levels of activity:

– Activity: responds to a need (materialistic or intellectual) – Why
– Actions: executed consciously to reach an explicit goal set by the subject – What
– Operations: executed unconsciously or semi-consciouly to execute actions – How

Activity theory

Levels of activity:

- Action -> operation: automation / internalisation
- Operation -> action: conceptualisation (e.g., in case of failure)
- Activity -> action: according to the context



Activity theory - applications

Activity-centric computing

Instead of a task-oriented analysis of practice,
analyze the *activities* people engage in
and the *tools* they use to conduct them

Analyze the division of labor

Support collaborative activities with different roles

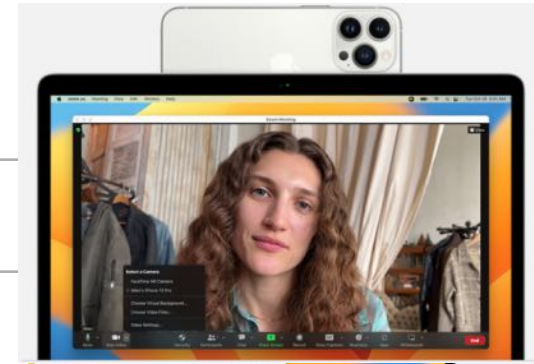
Analyze artifact ecologies

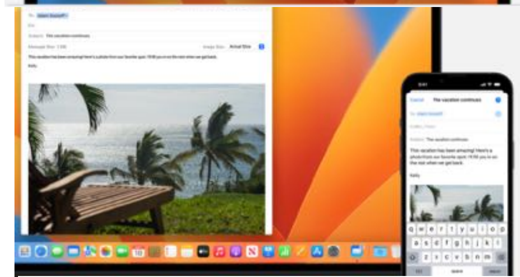
Support combinations of devices (digital and physical)

Apple Continuity

"All your devices, one seamless experience"

- Use iPhone as camera
- Use mouse/keyboard for tablet
- Use tablet for desktop
- AirPlay between devices
- Get messages across devices
- Unlock screen with watch
- Answer call on desktop
- Airdrop files across devices
- Copy-paste across devices
- Start editing on one device, finish on another
- Use phone as hotspot
- …





Thomas Green

Cognitive dimensions

Notation :

- Tool to help interaction designers
- Evaluating a system according to certain criteria
- Scientific foundation: importance of representation to solve a problem

6 types of activity:

- Incrementation : add data
- Transcription : copy from another source
- Modification : change content, adapt to a new problem
- Exploration : trial and error to find a solution
- Search: look for an object that may not exist
- Comprehension : discover an unknown aspect of the system

Thomas Green

Cognitive dimensions

Dimensions : aspects of the informational structure that can be analyzed according to the activity being studied.

Some examples :

- **Viscosity**: resistance to change
- **Visibility**: ability to see components easily
- **Premature commitment**: constraints on the order of actions
- **Hidden dependencies**: important but hidden links between entities
- **Role expressiveness**: the role of an entity is easy to infer
- **Abstraction**: types and availability of abstraction mechanisms
- **Consistency**: similar semantics are expressed with similar syntax
- etc.

Cognitive dimensions - applications

Walkthrough a design to assess each dimension

Example of **viscosity**

- Changing the travel date when looking for a train

Example of **premature commitment**

- Giving the name of a file when saving it

Example of **hidden dependency**

- Deleting a file when their are aliases pointing to it

Example of **abstraction**

- The notion of style to represent a set of attributes

Interaction

Morphological analysis of input devices [Card et al.]

UAN [Hartson]

GOMS [Card-Moran-Newell]

Instrumental interaction [Beaudouin-Lafon]

Morphological analysis of input devices

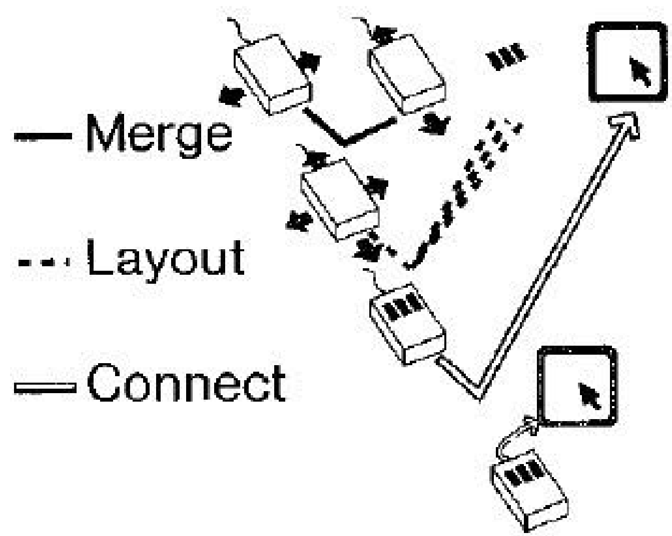
Description of the properties of an input device:

Transducer of physical properties into logical properties

- M = Manipulation operation
  - position/force, absolute/relative => P, F, dP, dF
  - linear/circular => X, Y, Z / rX, rY, rZ
- In = Input domain
- S = Current state of the device
- R = Resolution function: In -> Ou
- Out = Output domain
- W = Other properties of interest

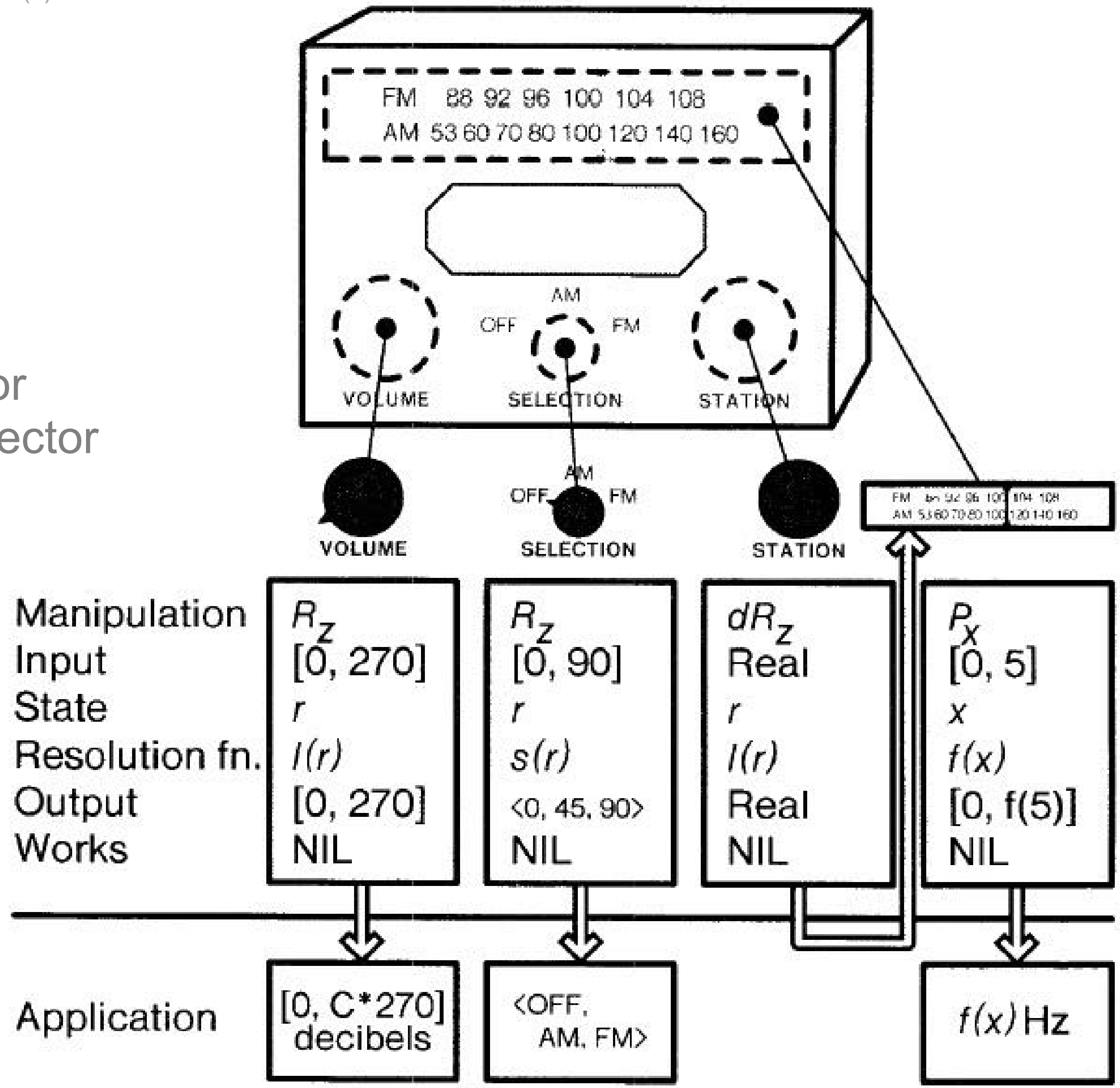
Composition of input devices:

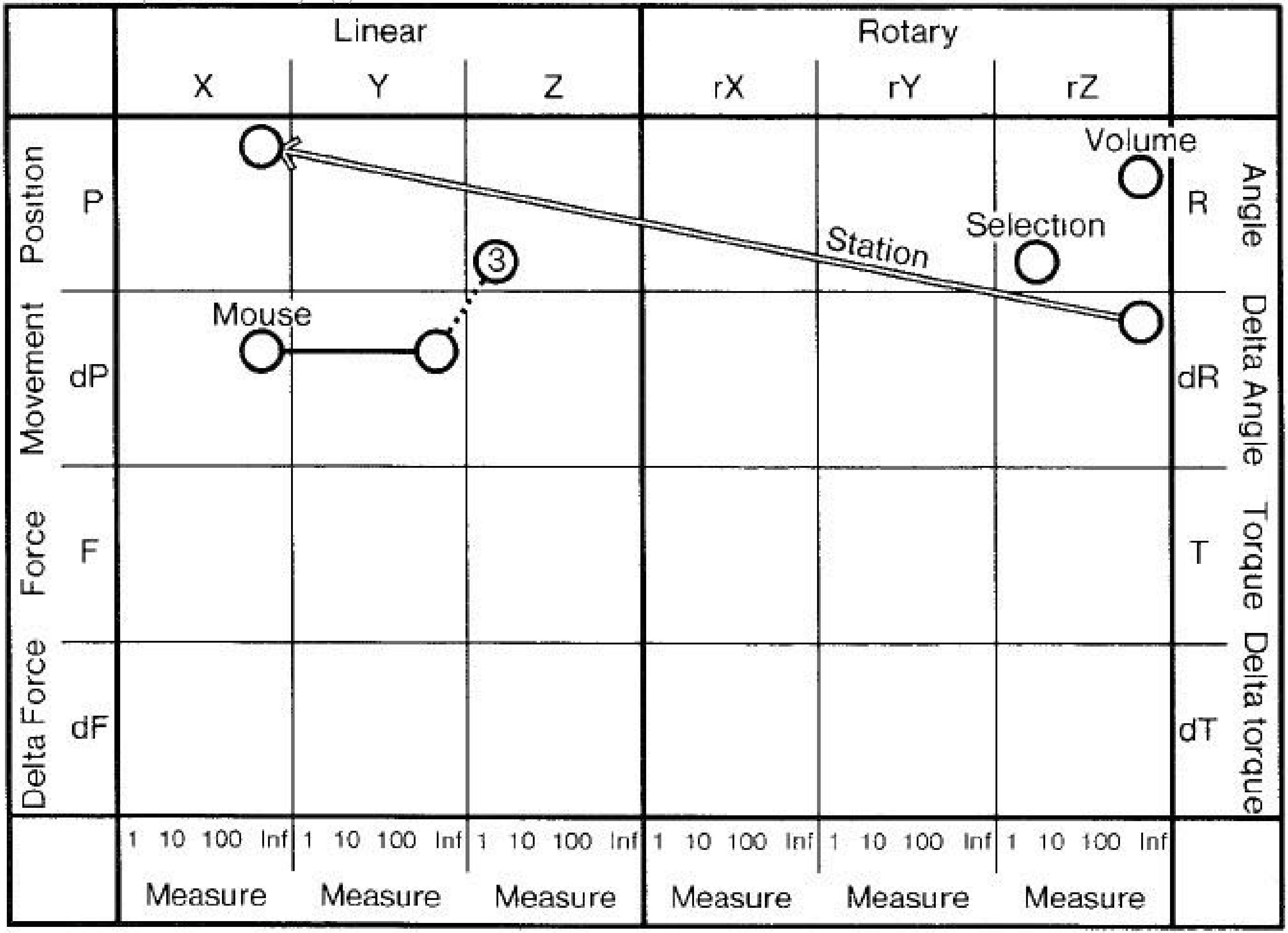
- Merge
- Layout
- Connect



Example

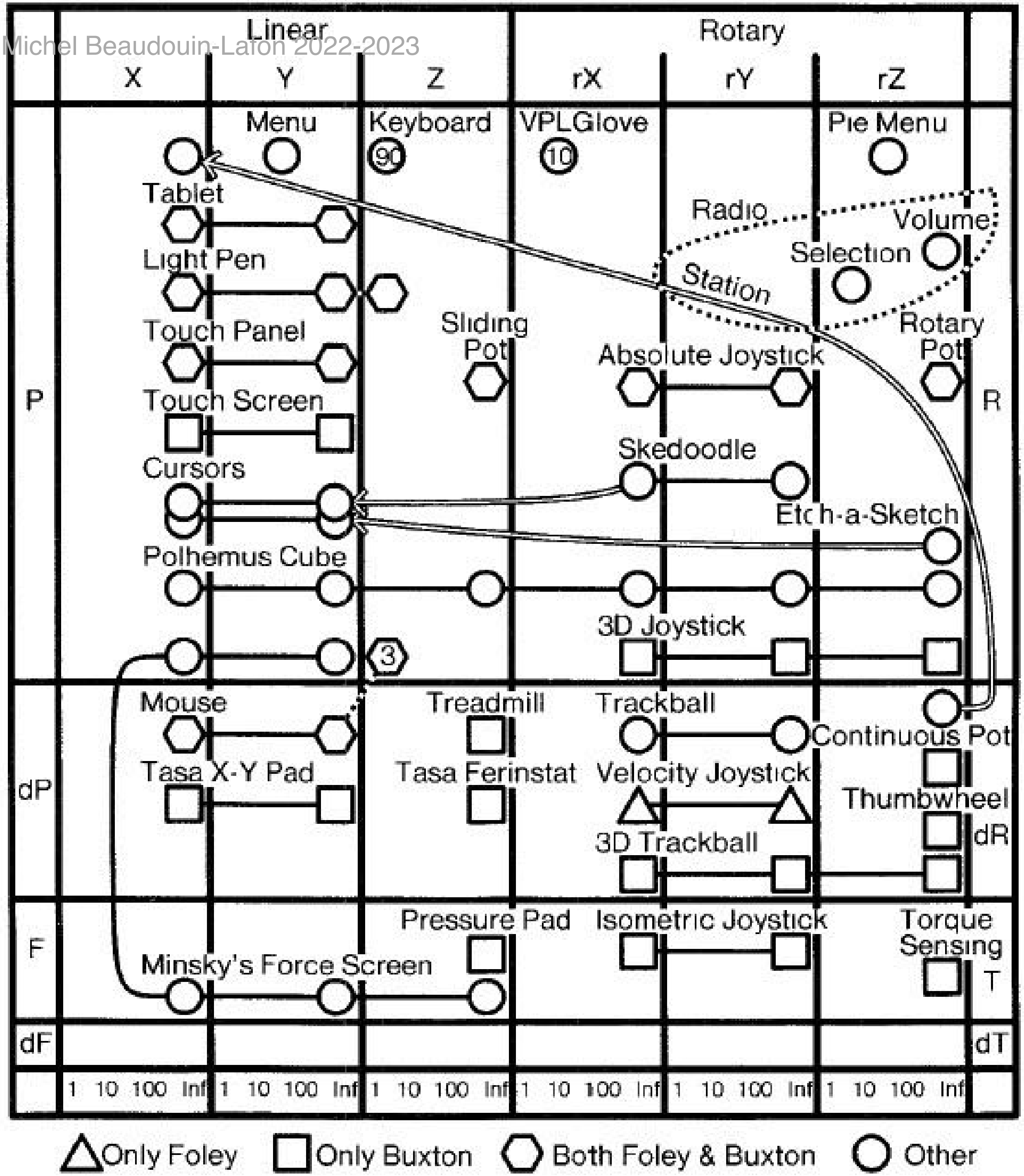
Radio :
- Volume dial
- AM/FM selector
- Frequency selector




Linear
Rotary
X
Y
Z
rX
rY
rZ
Position
P
Movement
dP
Force
F
Delta Force
dF
Angle
R
Delta Angle
dR
Torque
T
Delta torque
dT
Volume
Selection
Station
3
Mouse
1 10 100 Inf
Measure

Taxonomy

Comparison of input devices, including those studied by Foley and by Buxton



Siochi & Hartson

UAN : User Action Notation

Description of user actions and system responses

Example : selecting an icon

Action	Feedback
~[icon] Mv^	icon!

More accurate version:

~[icon] Mv	icon-! : icon! , all icon'! : icon'-!
M^	

Moving an icon:

~[file_icon] Mv	file_icon-! : file_icon! , all icon'! : icon'-!
~[x,y]* ~[x',y']	outline(file_icon) > ~
M^	@x',y' display(file_icon)

UAN

Action	Feedback	Interface state	Computation
~[file_icon] Mv	file_icon-! : file_icon! , all icon'! : icon'-!	selected = file	
~[x,y]* ~[x',y']	outline(file_icon) > ~		
M^	@x',y' display(file_icon)		pos(file_icon) = x',y'

Informal notation

- Usable with a standard keyboard
- Easy to remember
- Separates symbols from their meaning
- Can be extended if needed:
  - New symbols
  - New columns (e.g., cognitive load)

Card, Moran & Newell

The GOMS family of models

GOMS = Goals, Operators, Methods, Selection rules

- **G**oals: what the user wants to do
- **O**perators: actions supported by the software application
- **M**ethods: learned sequences of subgoals and operators to reach a goal
- **S**election rules: users' personal rules to choose one of several methods

GOMS is both:

- A method to describe user tasks
- A set of descriptive (and sometimes predictive) models, used at several levels of abstraction

Task analysis techniques based on models of information processing

Example : move a sentence in a text

Initial goal: edit text

Sub-goal: select text to move

Operators:
a. move the mouse
b. clic mouse button
c. enter key on keyboard

Methods:
- For editing:
  1. Delete sentence and type again
  2. Cut-paste using keyboard shortcuts
  3. Cut-paste using menu items
- For selection :
  4. Click and drag text
  5. Double-click first word, shift-click last word

Selection rules:
- For editing: method 1 if the text is short, method 2 if the user knows the shortcuts, method 3 otherwise.
- For selection: method 4 if the text to be moved is not a set of complete words, method 5 otherwise.

KLM : Keystroke-Level Model

Operators in the original version:

- K – hit key or button (0.08s - 1.20s, mean 0.40s)
- P – pointing a target with the mouse (1.10s)
- H – Homing = moving hand between mouse and keyboard (1s)
- D – Drawing a line segment (0.9n + 0.16l, n segs de long. l)
- M – Mental activity to prepare for next action (1.35s)

“Magical” rules for placing operator M

Example : Method 5 then 3

- Selection: M PK PK
- Copy command: M PK PK
- Select destination: M PK
- Paste command: M PK PK

total = 14.9s

CMN-GOMS : Card-Moran-Newell GOMS

Evolution of the Keystroke-level model

- Some additional operators
- Computer support
  - Automatic evaluation of predicted times
  - Automatic evaluation of selection rules

Predictive model (as is KLM)

- Helps compare various methods for a single task
- Example : shows that the selection rule for moving the cursor with the mouse vs. the keyboard tends to choose the optimal method.

Problem: tendency to overestimate execution times

- Operators have a fixed duration
- Learning is not taken into account

Bonnie John

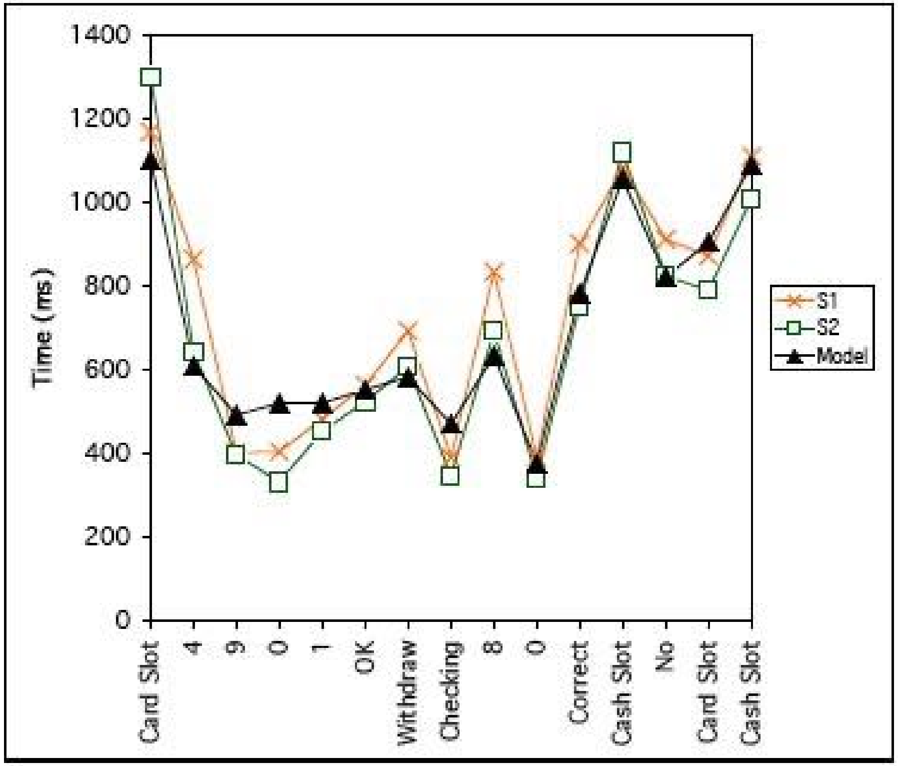
CPM-GOMS : Critical-Path Method

Based on the Model Human Processor (MHP)

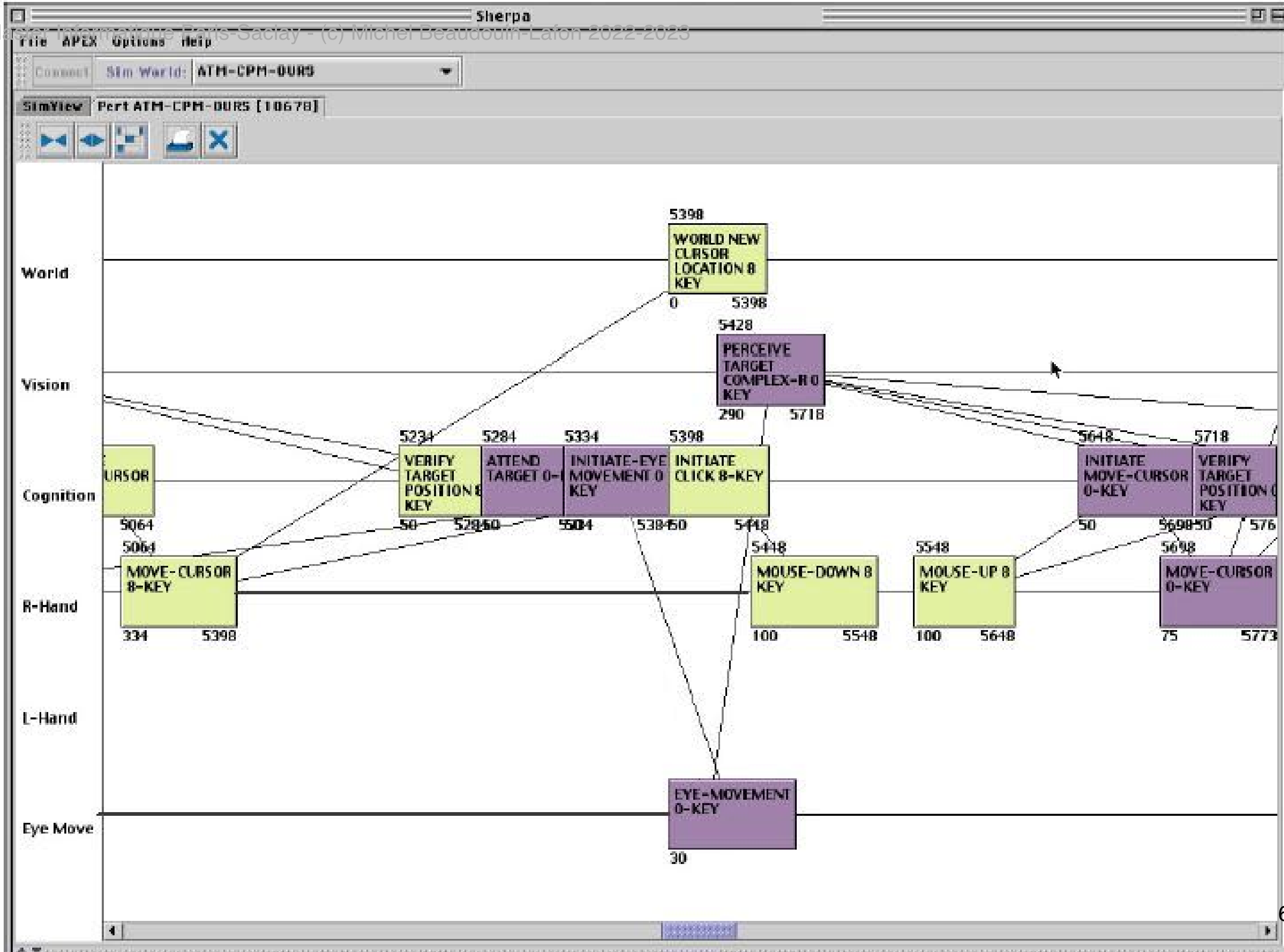
- Parallel processing of perceptual, cognitive and motor activities
- PERT diagram created from the CMN-GOMS description of the task using templates of MHP operators for elementary tasks

Predictive power:

- Performance prediction is more accurate than KLM
- Qualitative analysis using the critical path in the PERT diagram



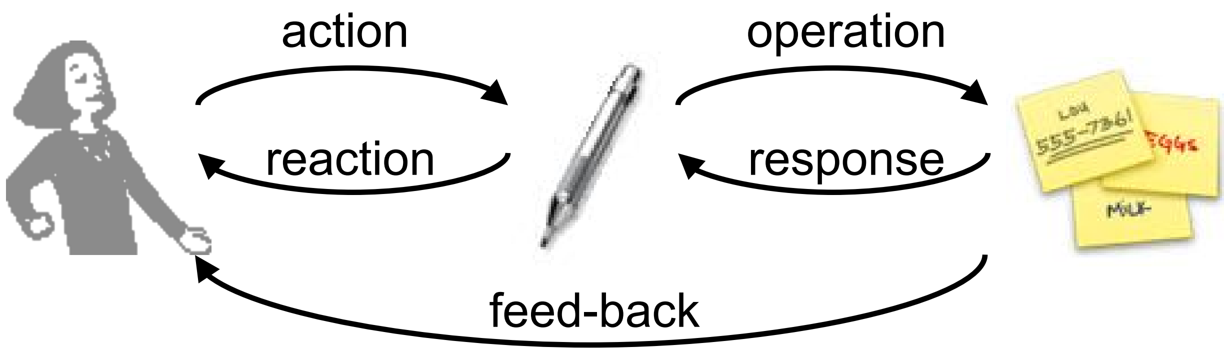
APEX : tool that automates the creation of diagrams


Sherpa
File APEX Options Help
Connect Sim World: ATM-CPM-OURS
SimView Pert ATM-CPM-OURS [10678]
World
Vision
Cognition
R-Hand
L-Hand
Eye Move
WORLD NEW CURSOR LOCATION 8 KEY
PERCEIVE TARGET COMPLEX-R 0 KEY
VERIFY TARGET POSITION 8 KEY
ATTEND TARGET 0-
INITIATE-EYE MOVEMENT 0 KEY
INITIATE CLICK 8-KEY
INITIATE MOVE-CURSOR 0-KEY
VERIFY TARGET POSITION KEY
MOVE-CURSOR 8-KEY
MOUSE-DOWN 8 KEY
MOUSE-UP 8 KEY
MOVE-CURSOR 0-KEY
EYE-MOVEMENT 0-KEY

Beaudouin-Lafon

Instrumental Interaction

Interaction model
- Describes an interface in terms of *domain objects* and *instruments*



Descriptive aspect
- Covers a large set of existing techniques (GUI, tangible, AR, ...)

Predictive aspect
- Properties for comparing instruments
  - Degree of indirection, degree of integration, degree of compatibility

Generative aspect
- Design principles: reification, polymorphism, reuse

Software architecture models

Seeheim

MVC - Model-View-Controller

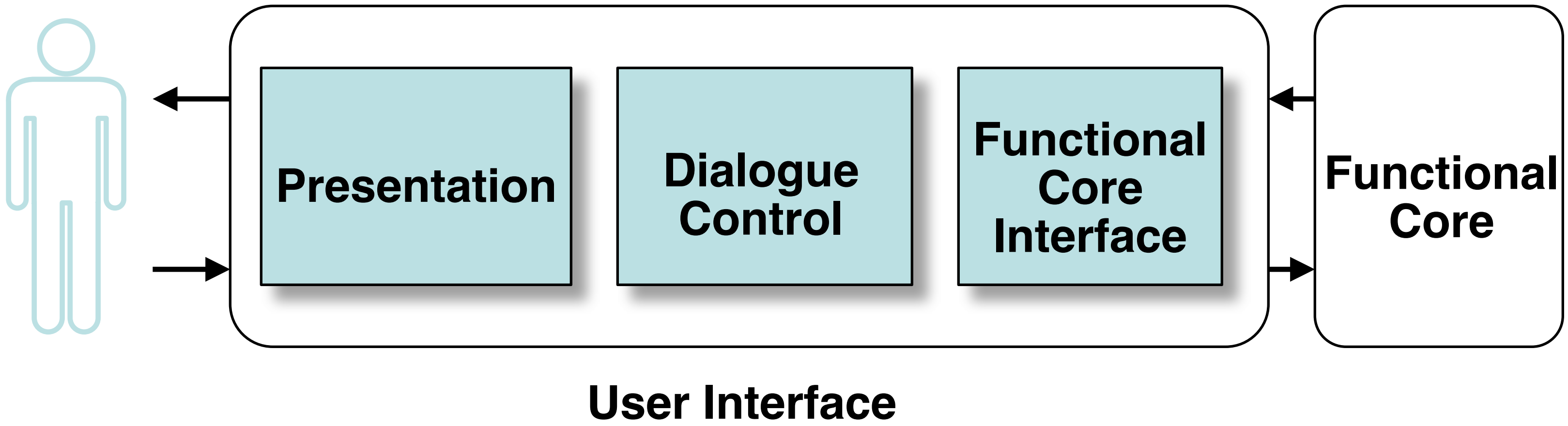
Arch

PAC - Presentation-Abstraction-Contrôle [Coutaz]

MVVM

State machines [Newman]

Seeheim

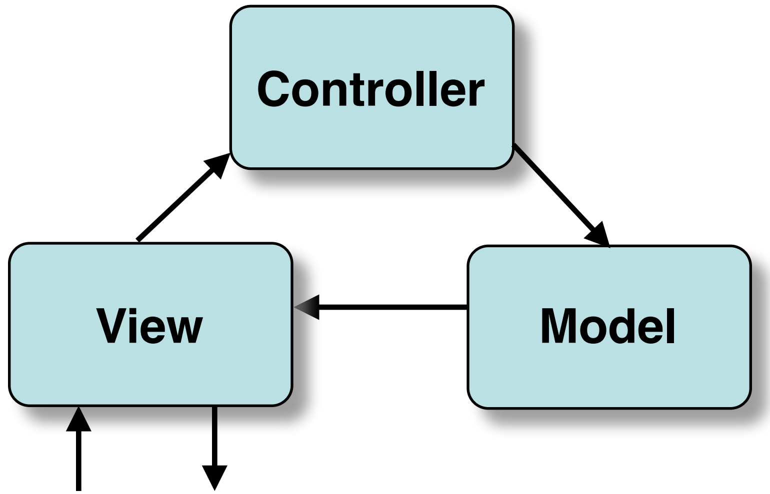


Presentation
- Manages input and display at a low level

Dialogue control
- Validates input and transforms it into commands
- Transforms responses from the Functional Core into graphical entities

Functional core interface
- Adapts the functional core to the needs of the interface

MVC - Model-View-Controler

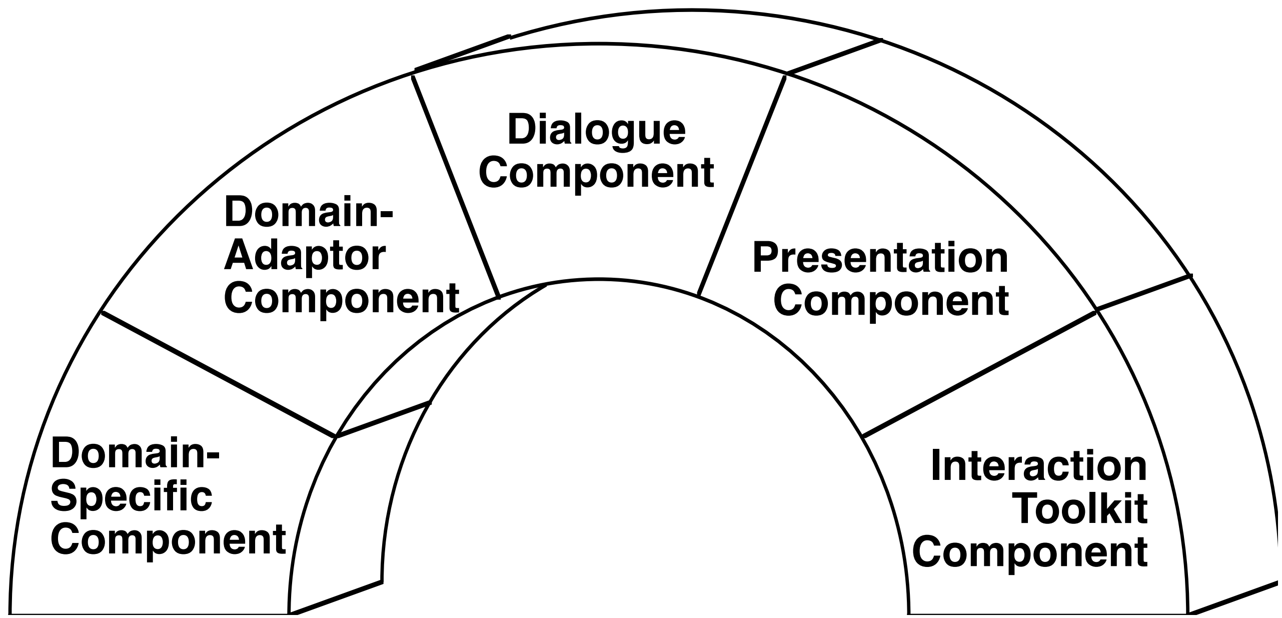


Interface = hierarchical composition of MVC triplets

- Model: abstract representation of the interactive object
- View: graphical representation and input management
- Controler: updates the model when the view is edited

Implemented originally in the Smalltalk system

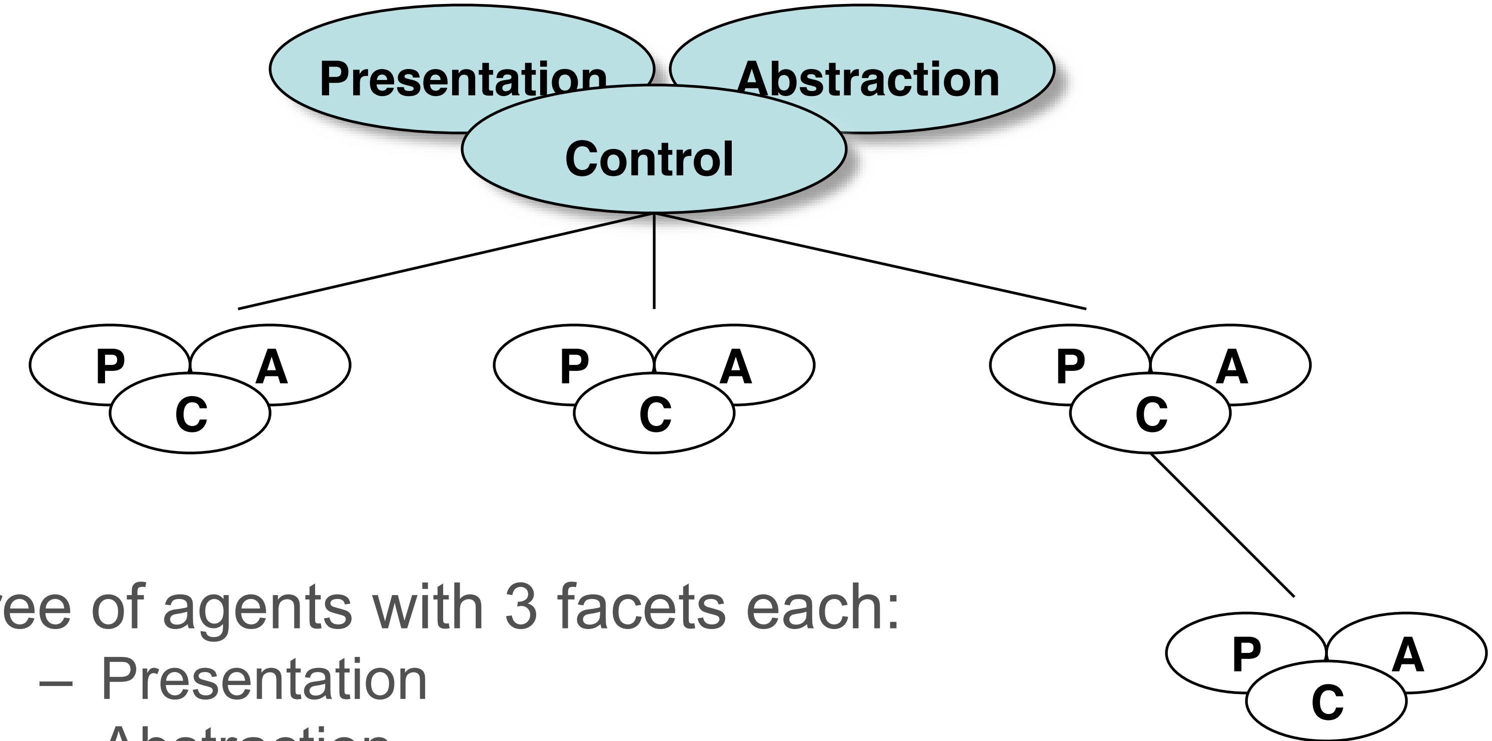
Arch



Modern version of Seeheim
- Acknowledges the existence of user interface toolkits
- Adaptators
  - On the presentation side
  - On the functional core side
- Components can be of different sizes, or even non-existant

Joëlle Coutaz

PAC - Presentation-Abstraction-Control



Tree of agents with 3 facets each:

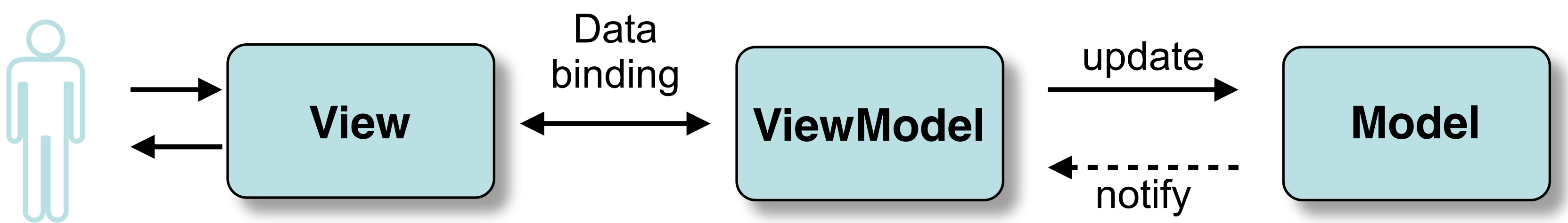
- Presentation
- Abstraction
- Control

Heuristics for the structure of the tree (e.g., multiple views)

Abstract model: no software platform (unlike Smalltalk for MVC)

Numerous evolutions: PAC-Amodeus, PAC*, CoPAC, etc.

MVVM - Model-View-ViewModel



Modern variant of MVC

The View manages the visual representation and user input

The Model holds the application state

The ViewModel abstracts out the state of the ViewModel

Data binding automates the synchronization
between View and ViewModel

Software architecture models - applications

User interface toolkits / frameworks

Java Swing is based on MVC

JavaFX is based on MVVM

Web frameworks:

- React, Angular, Vue are based on MVVM
- The View is provided by HTML/CSS
- The Model is provided by the application
- The ViewModel is provided by the framework and uses data binding to automate updates

State machines

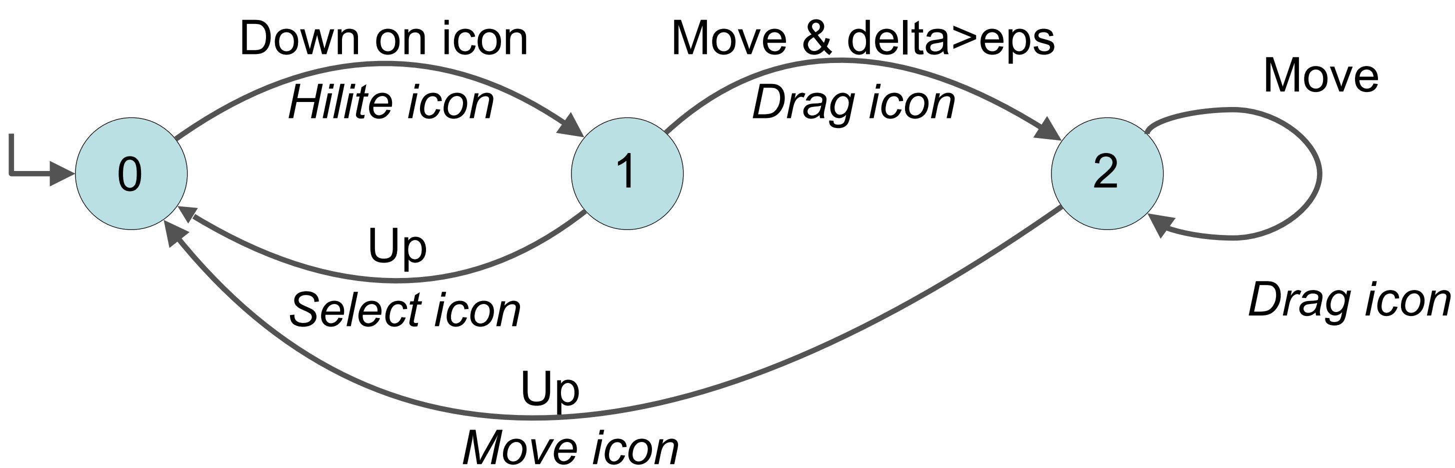
Formal description of the behavior of the interface

Extend finite state automata or transition networks:

- ATN (augmented transition networks)
- RTN (recursive transition networks)
- Statecharts (Harel)
- Petri nets

Proof and validation of properties is possible

Direct link to implementation



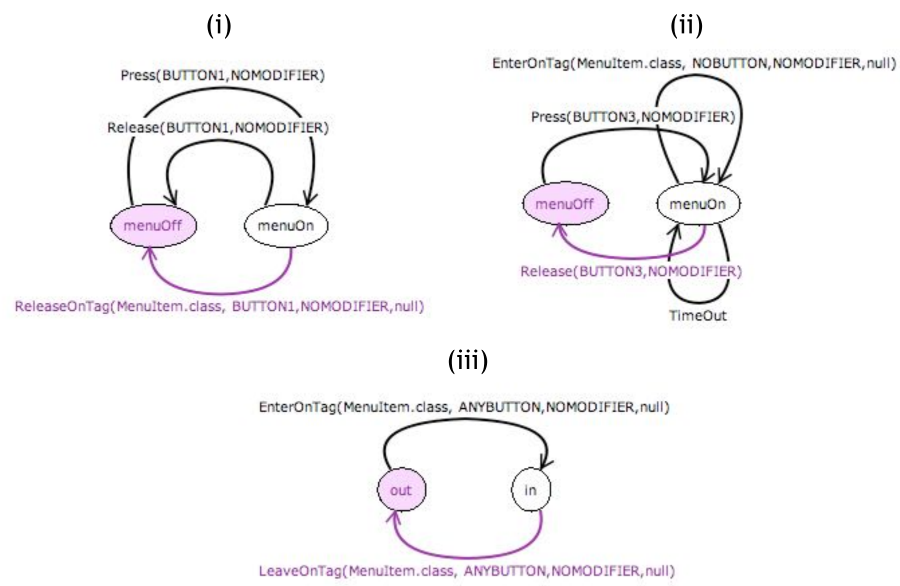
Appert & Beaudouin-Lafon

State machines - application

SwingStates library:

Describe interaction with state machines rather than event listeners / callbacks

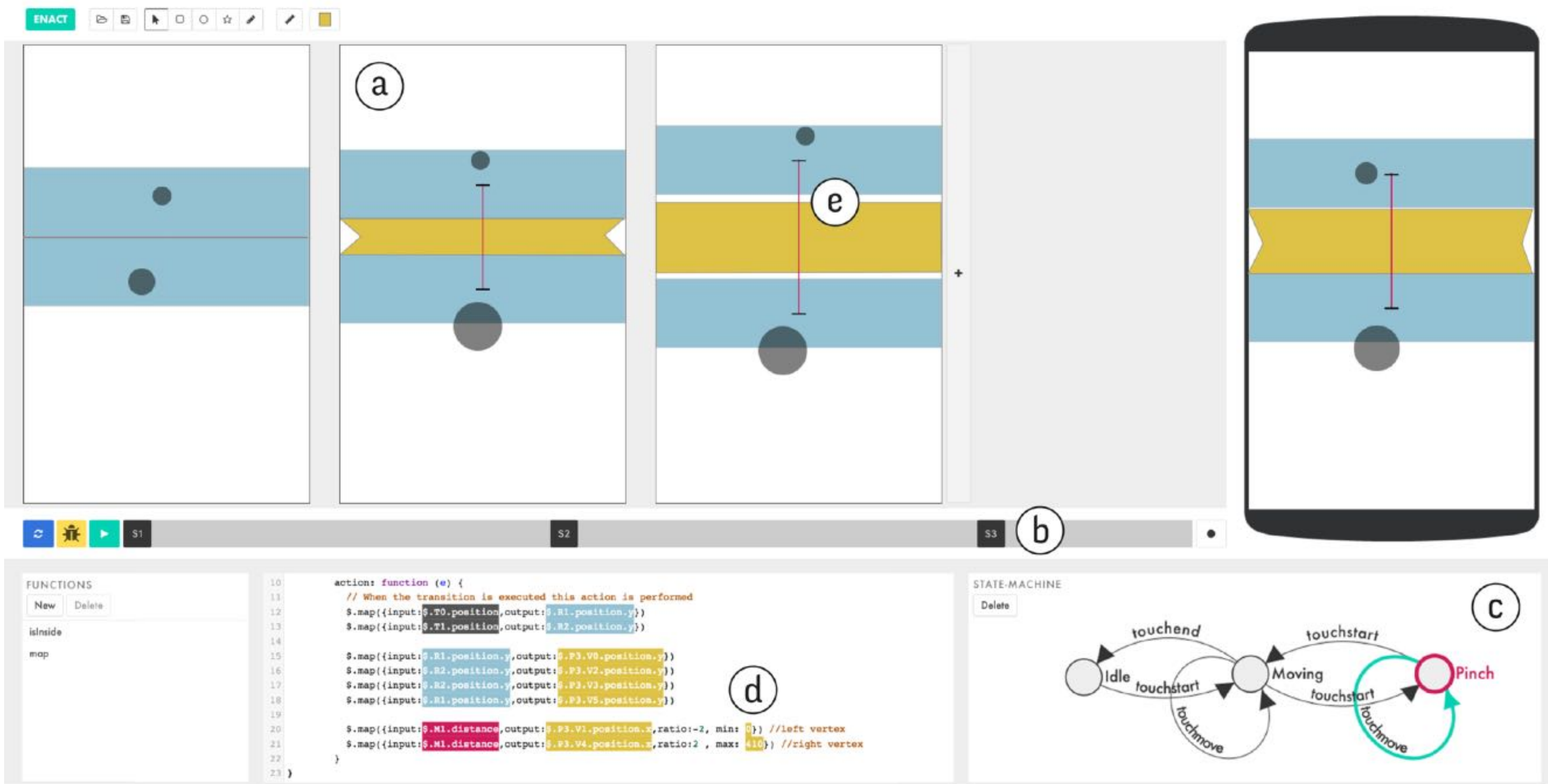
```
StateMachine   sm = new StateMachine() {
  SMShape dragged = null;
  public State  start  = new State() {
    Transition  dragOn  =
       new PressOnShape(BUTTON1,  "drag") {
         public void action() {
           dragged = getShape();
         }
    };
  };
  public State  drag  = new State() {
   Transition  drag  = new Drag(BUTTON1,  "drag") {
      public void action() {
        move(dragged);
      }
    };
    Transition  dragOff  =
      new Release(BUTTON1,  "start") { } ;
  };
};
```



Leiva, Maudet, Mackay, Beaudouin-Lafon

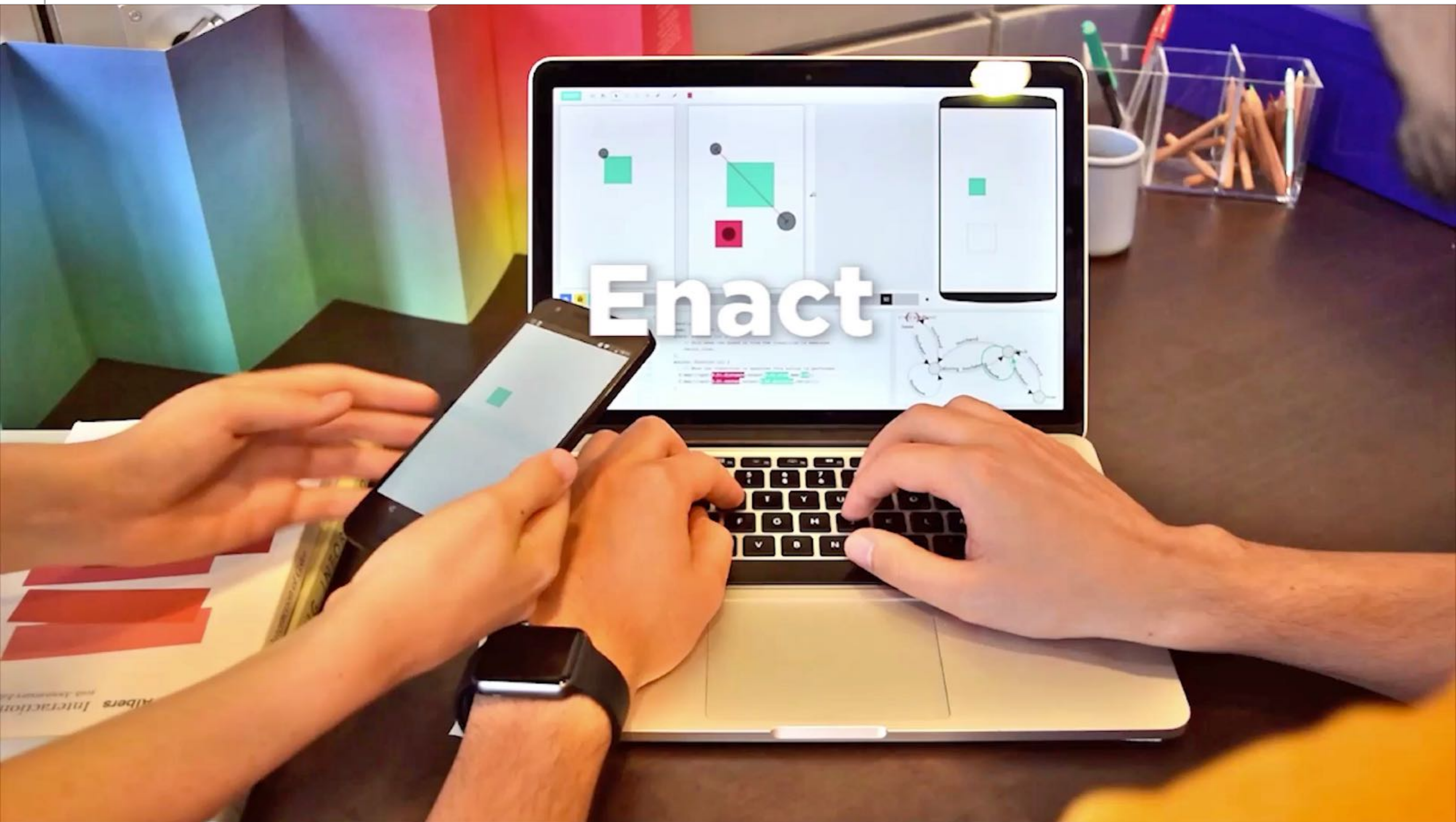
State machines - application

- ENACT: support designer-developer collaboration
  - Create touch-based interaction interactively



Leiva, Maudet, Mackay, Beaudouin-Lafon

ENACT



Conclusion

Models and theories in human-computer interaction

- Borrowed from Psychology
  - Action/Perception, Cognition
- Borrowed from Sociology
  - Ethnomethodology
- Borrowed from Computer Science
  - Automata
- Specific to HCI
  - GOMS, Instrumental Interaction

Models and theories in HCI are more often descriptive than predictive, and they are rarely generative

Bibliography

HCI Models, Theories, and Frameworks
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