### Information theory meets human-computer interaction

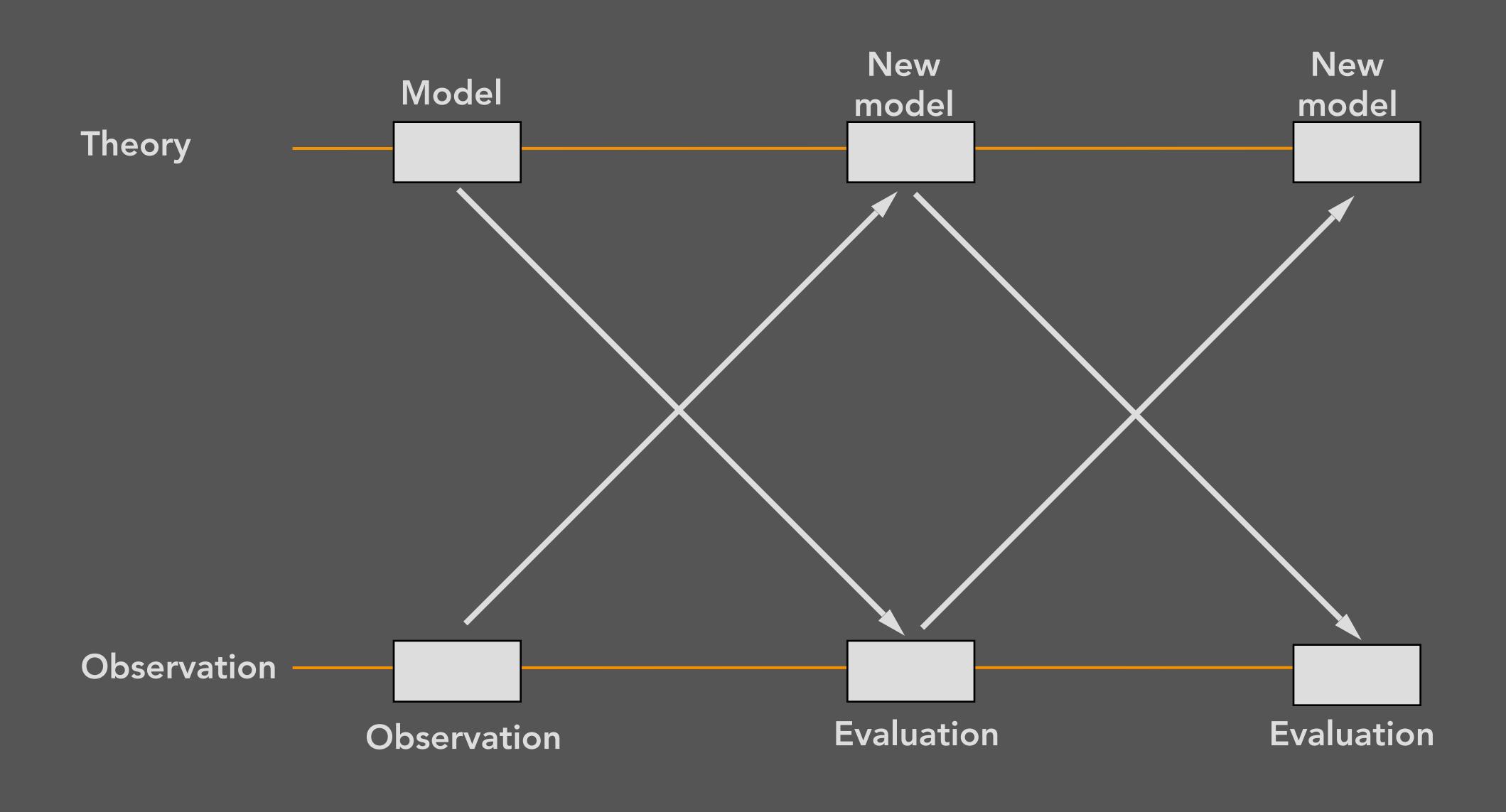
Michel Beaudouin-Lafon Université Paris-Saclay

SystemX 15 mars 2023

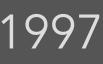
Theory in Human-Computer Interaction



### Theory in Natural Sciences

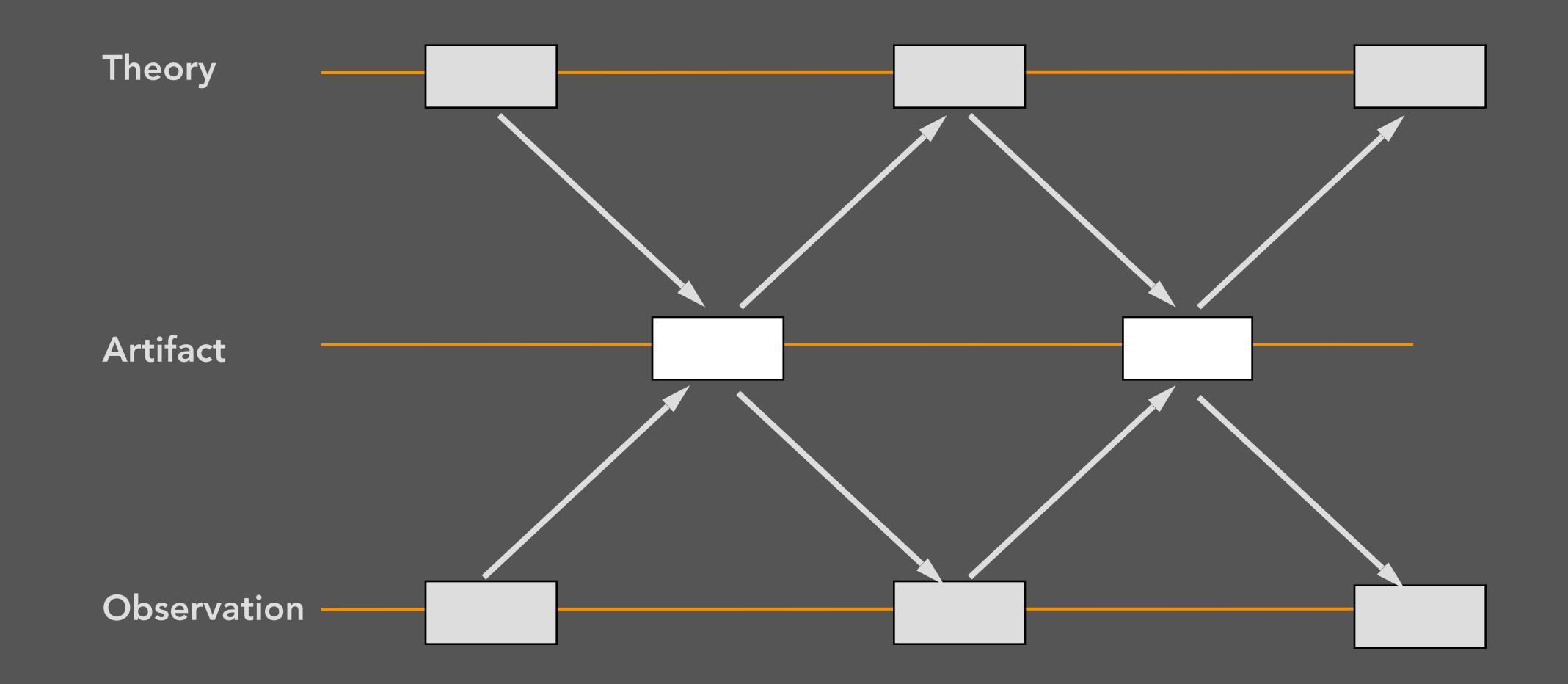


#### Mackay & Fayard, 1997

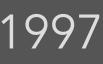




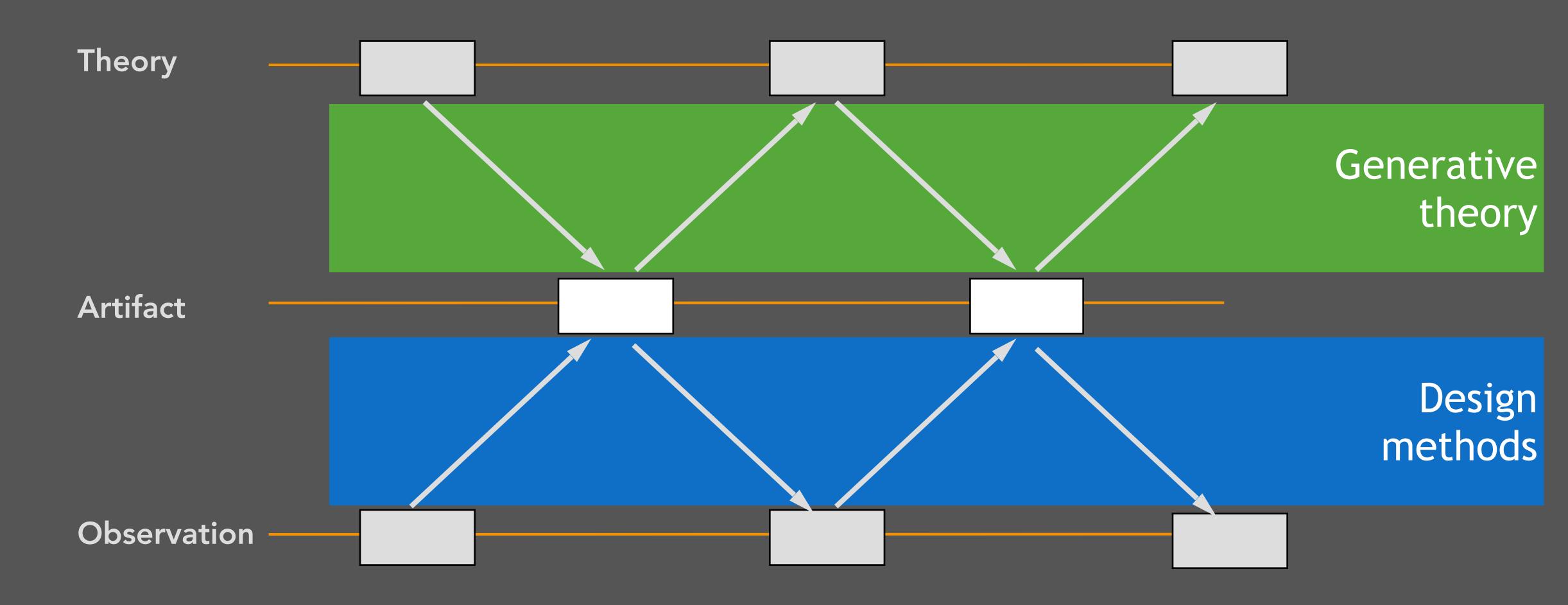
### Theory and HCI



#### Mackay & Fayard, 1997

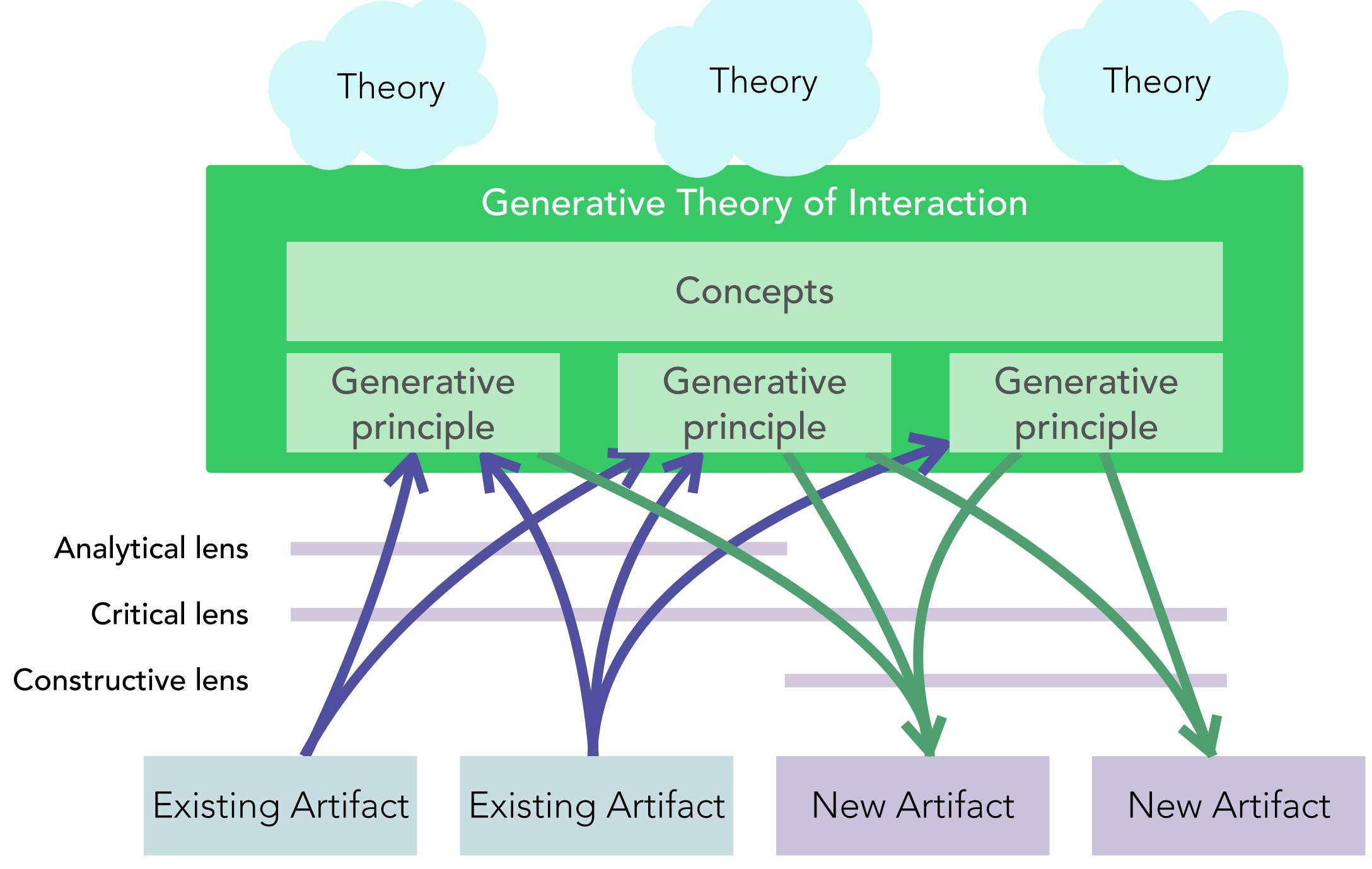


### Theory and HCI



#### Beaudouin-Lafon, Bødker & Mackay, 2021



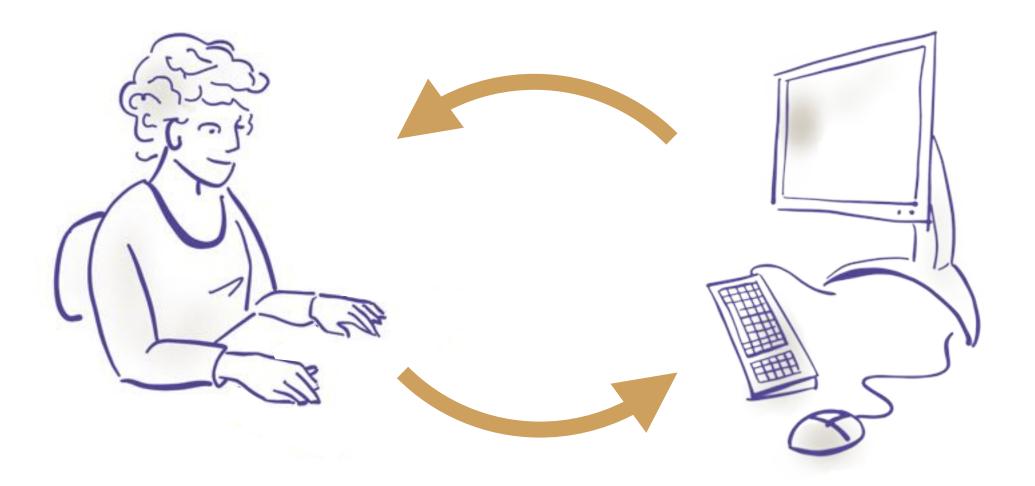




## Information



## Interaction as a phenomenon



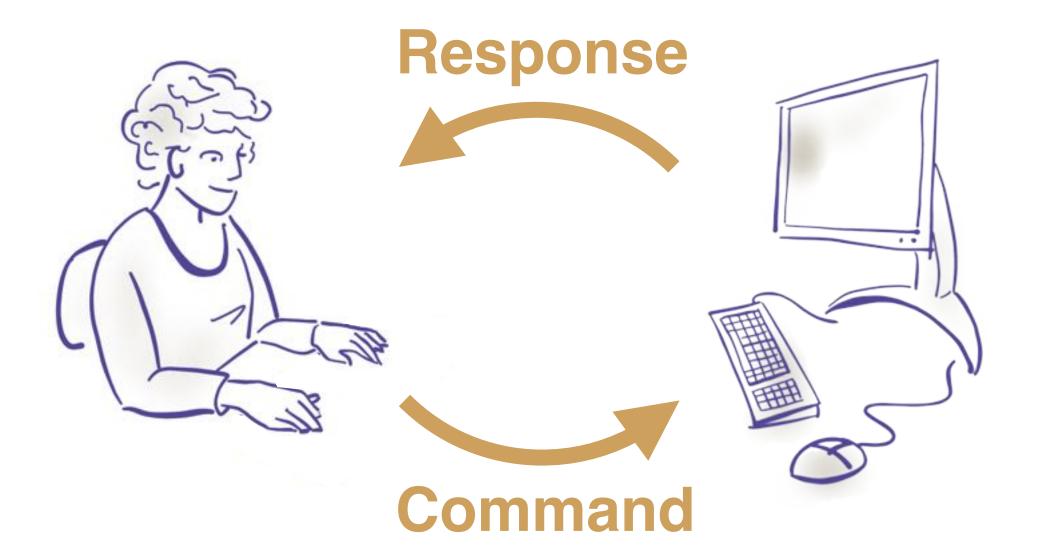
### What is sent by the user to the computer?

What is sent by the computer to the user?



8

## Interaction as a phenomenon

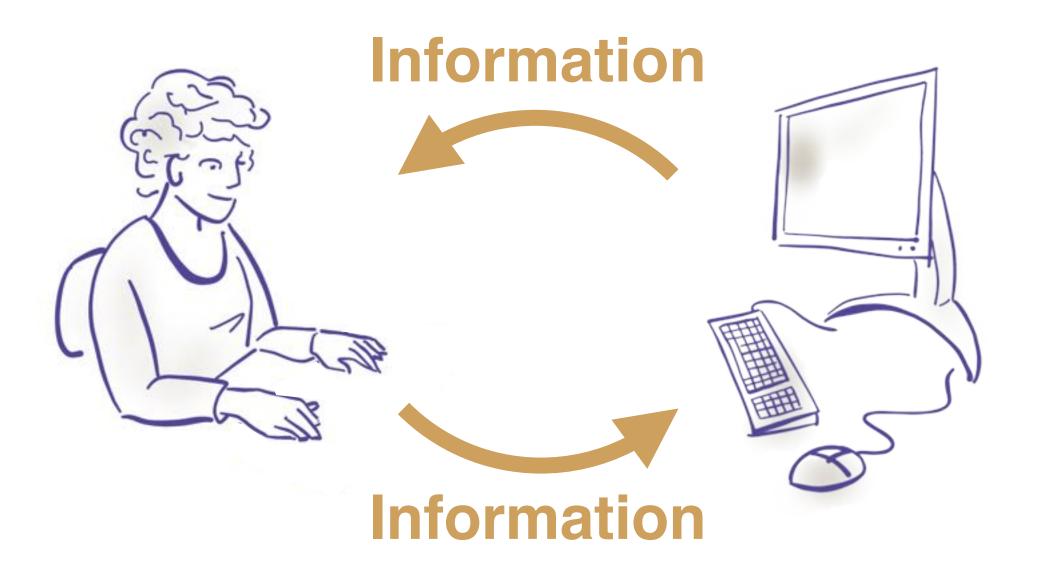


### What is sent by the user to the computer?

What is sent by the computer to the user?



## Interaction as a phenomenon



What is sent by the user to the computer?

What is sent by the computer to the user?

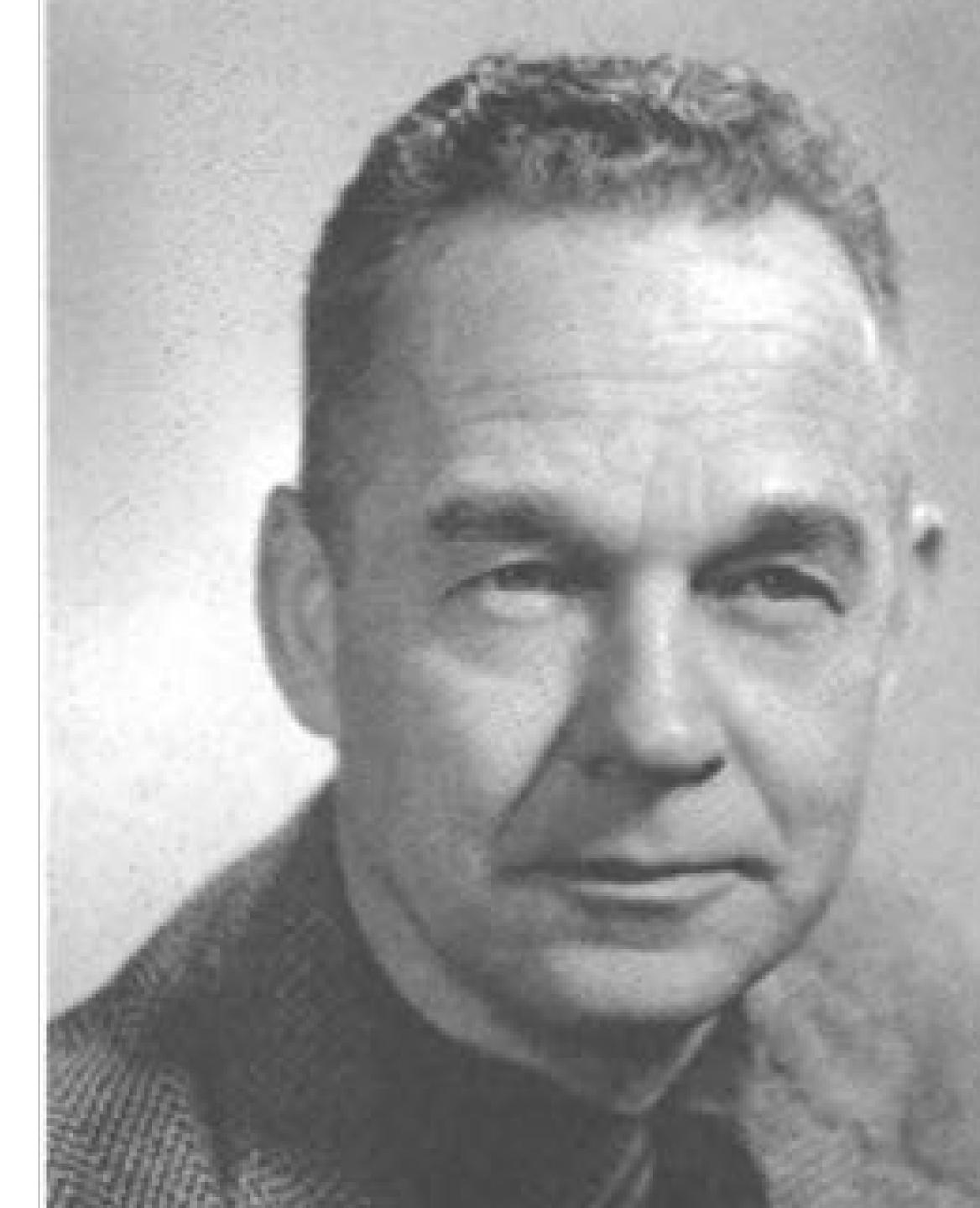
Interaction as information communication

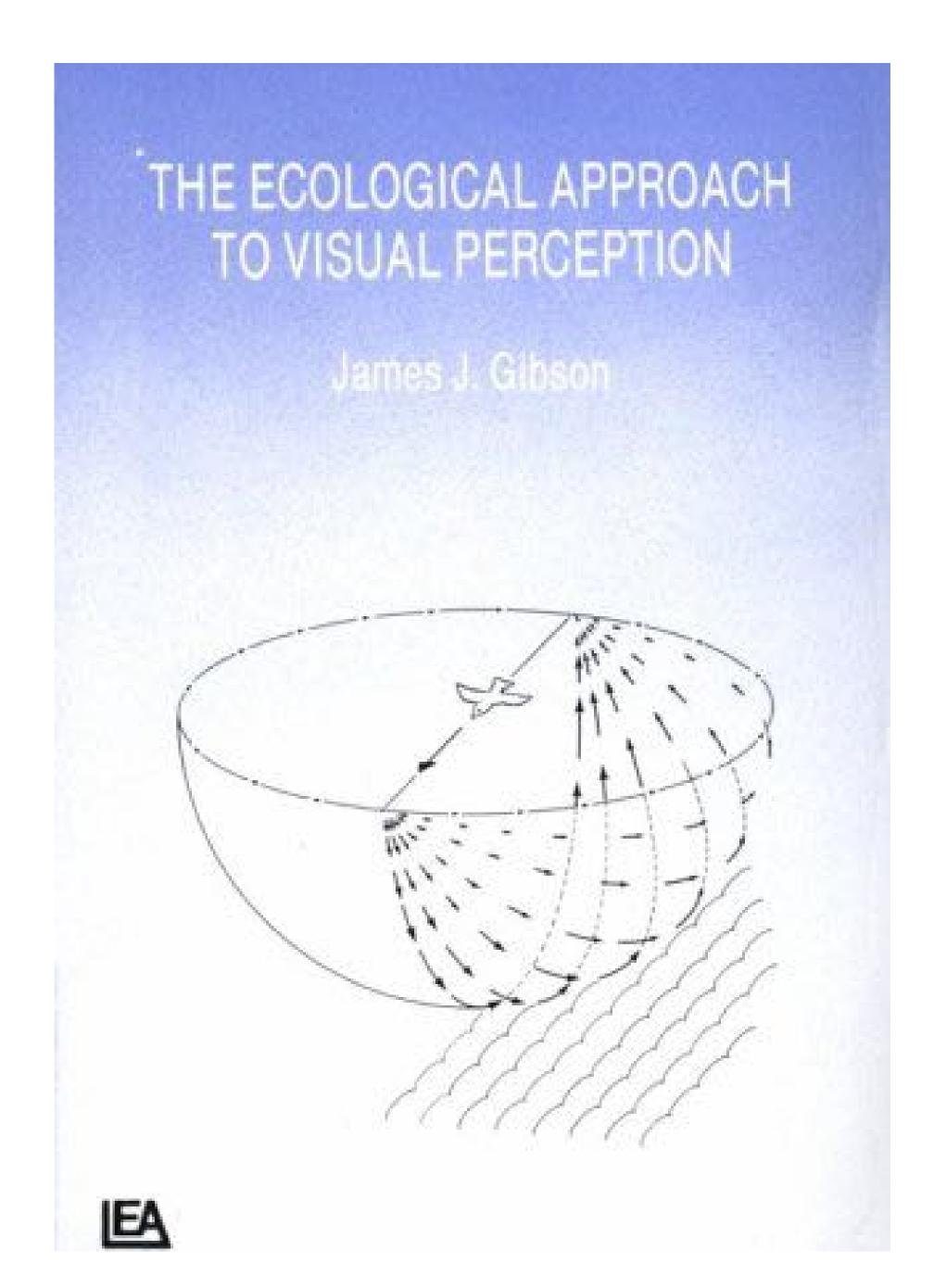


### James Gibson

## Ecological perception (1979)

Known in HCI for the notion of "affordance"





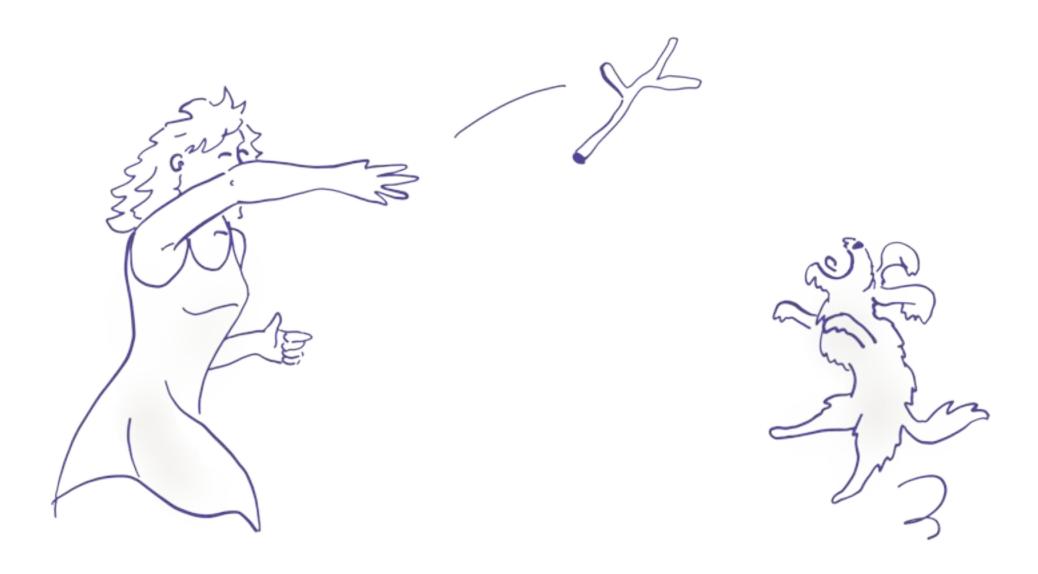
Co-evolution between organism and its environment

"Elegant" perceptual processes

Information is in the optical array and the optical flow

"Information pickup"



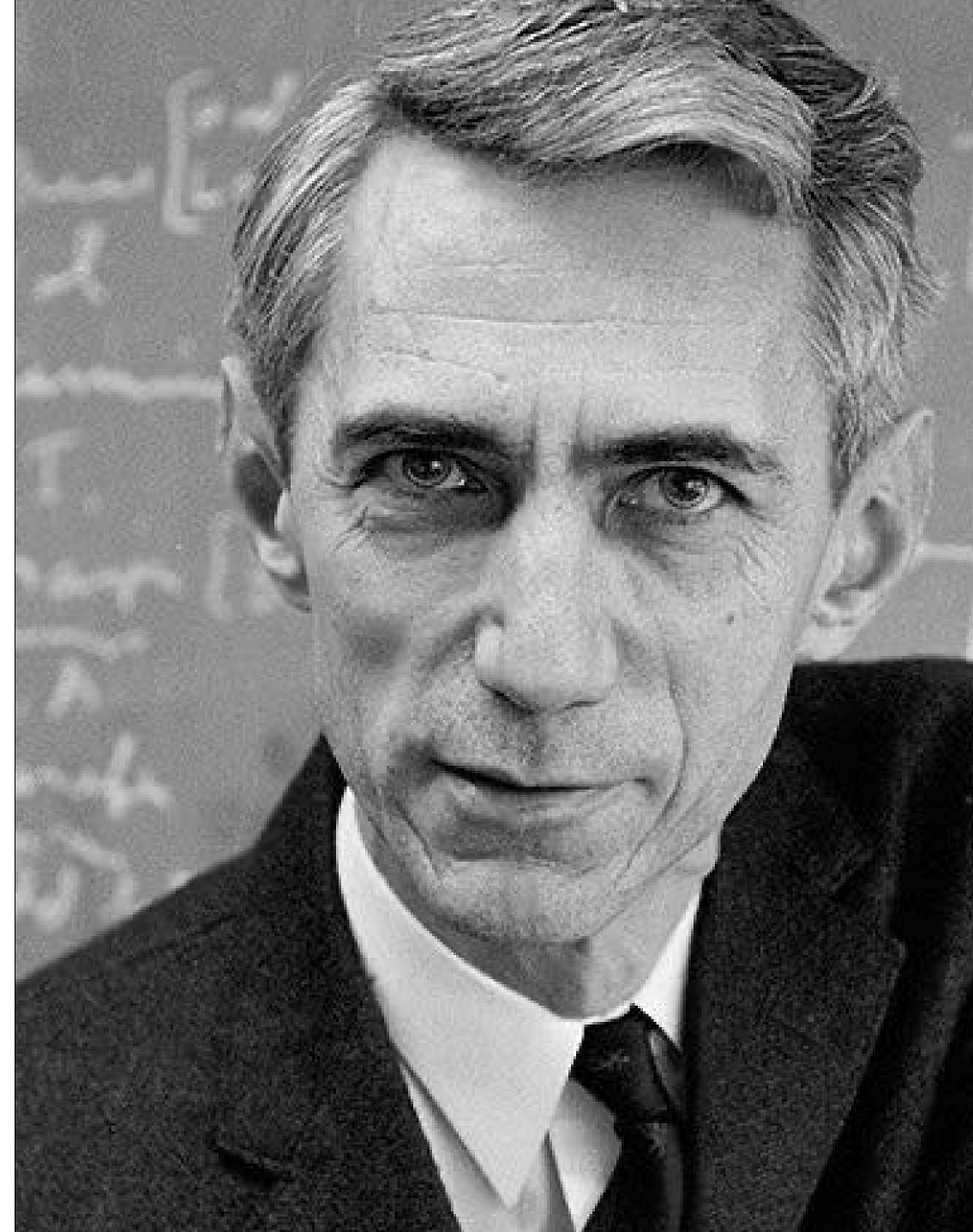


## The organism is equipped to extract invariants

#### Action-perception coupling act to perceive perceive to act

### Claude Shannon

## Theory of information (1948)



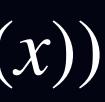
# Concept of information

Information reduces uncertainty

### Information carried by an event x of probability p(x):

$$h(x) = \log_2(1/p(x)) = -\log_2(p(x)) = -\log_2(p(x$$

Draw a coin: h(heads) = 1 bit Draw a dice: h(3) = 2.58 bits





# Concept of entropy

A measure of uncertainty

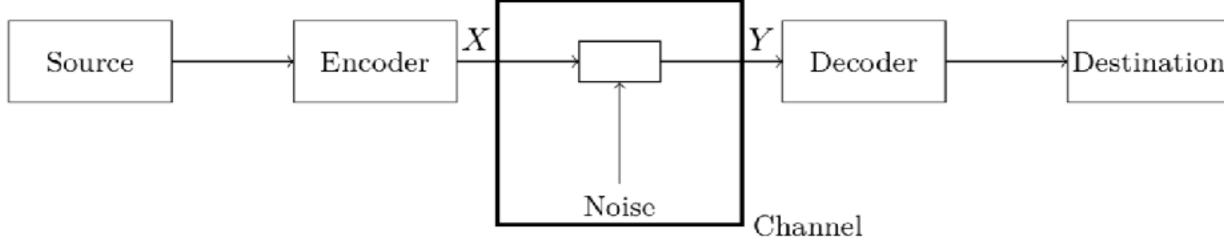
### Entropy of a random variable: $H(X) = -\sum_{x} p(x) \log_2 p(x)$

Entropy is maximal when the distribution p(X) is uniform

English text: entropy between 0.6 and 1.3 bits per character



### Information transmission

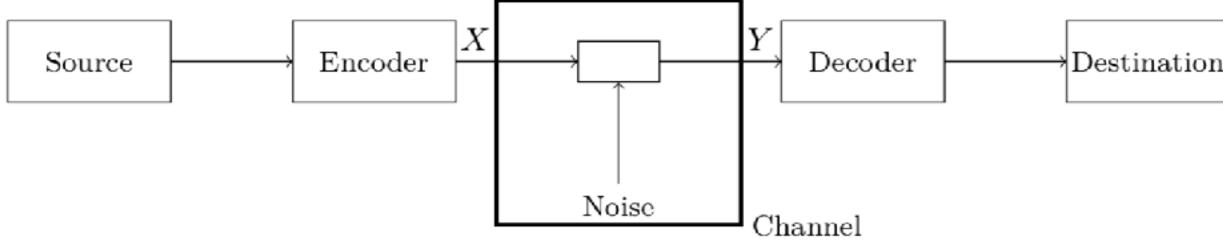


#### Entropy of a random variable: $H(X) = -\sum p(x)\log_2 p(x)$ ${\mathcal X}$

**Transmitted information:** I(X; Y) = H(Y) - H(Y|X)

#### some information is lost

### Shannon's theorem 17



#### Capacity of a channel subject to Gaussian noise:

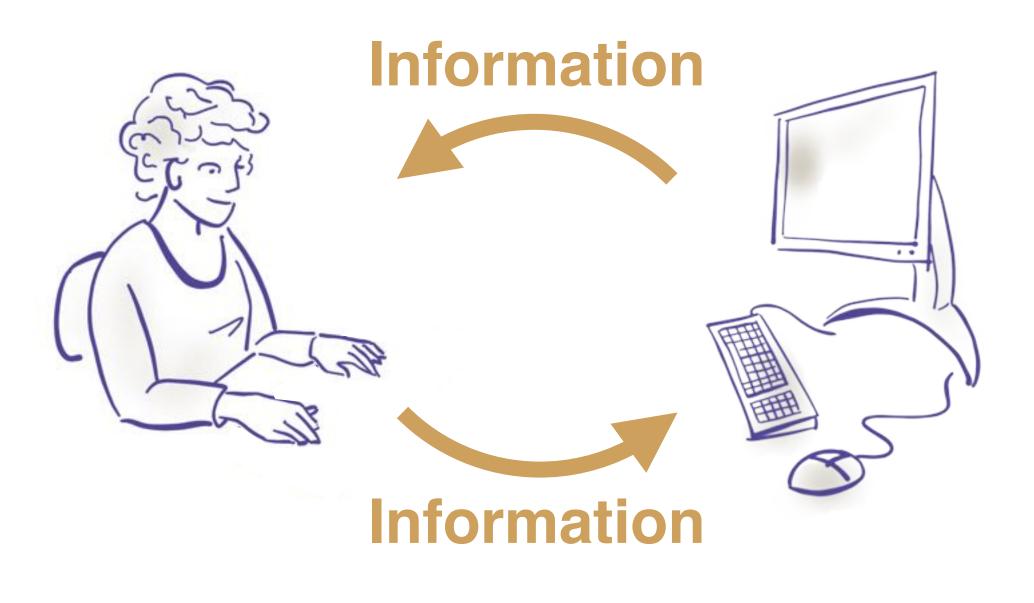
$$C = B_W \log_2 \left( 1 + \frac{P}{N} \right)$$

C is measured in bits/second

Maximum transmitted information



## What information?



#### User -> computer message (commands) -> Shannon

#### Computer -> User view -> Gibson

## Pointing





### Pointing



#### The most frequent task in GUIs

Many targets, some very small

Trade-off between speed and precision

Cost of error can be high

### Pointing



#### If the computer knew where I want to point, it could do it for me

Pointing performance is limited by human capabilities





### Paul Fitts

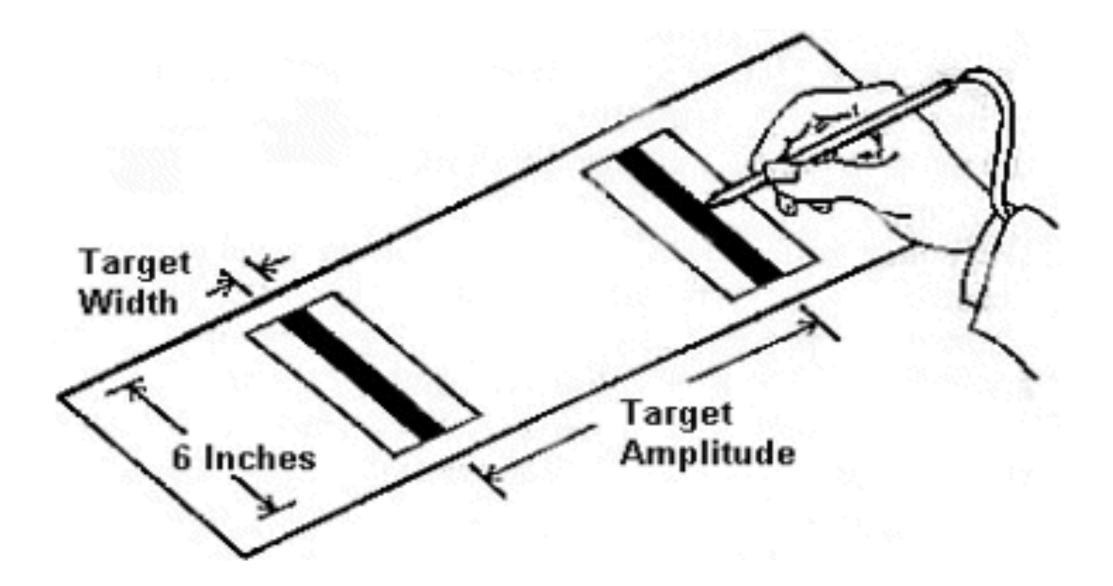
Psychologist

Also a pioneer in aviation safety

HAGA-MAGA list



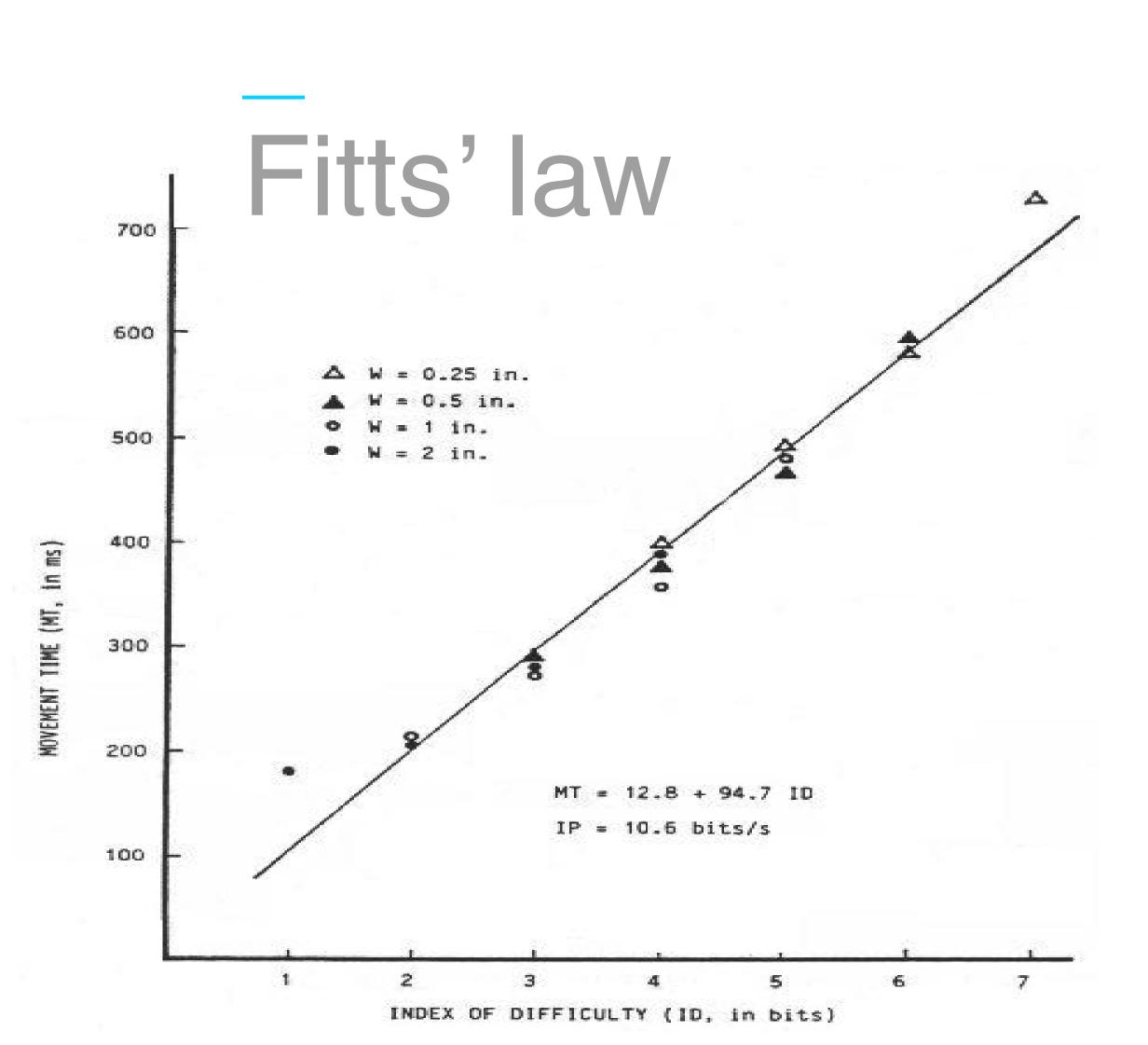
### Fitts' law (1954)



Speed-precision trade-off in aimed movements

D = distance to targetW = target width





Speed-precision trade-off in aimed movements

D = distance to target W = target width

 $MT = k \times ID$ movement time ID = log(1 + D/W) index of difficulty







### Fitts' law

#### A tool to compare pointing devices or pointing techniques

#### **Speed-precision trade-off** in aimed movements

D = distance to target W = target width

 $MT = k \times ID$ movement time ID = log(1 + D/W) index of difficulty





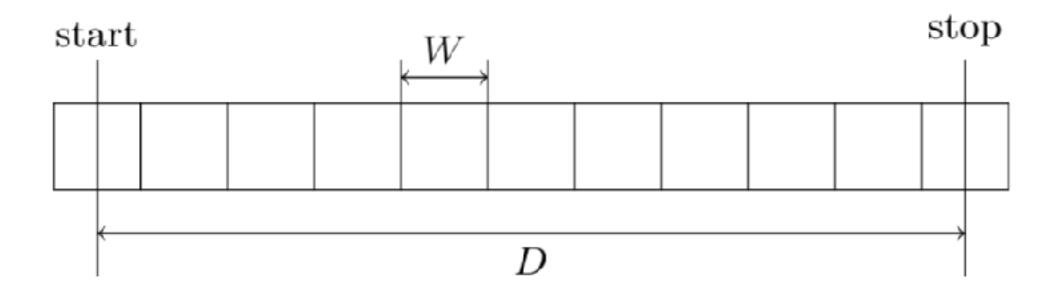


### Shannon meets Fitts

### Parallel between $MT = k \log_2 \left( 1 + \frac{D}{W} \right)$ and $C = B_W \log_2 \left( 1 + \frac{P}{N} \right)$

#### Distance = Signal Width (tolerance) = Noise

### Shannon meets Fitts



#### Aiming is choosing

$$X = -\frac{D}{2}, -\frac{D}{2} + W, \dots, \frac{D}{2} - W,$$
$$H = \log_2\left(1 + \frac{D}{W}\right) = ID$$

Index of difficulty = source entropy

No transmission!



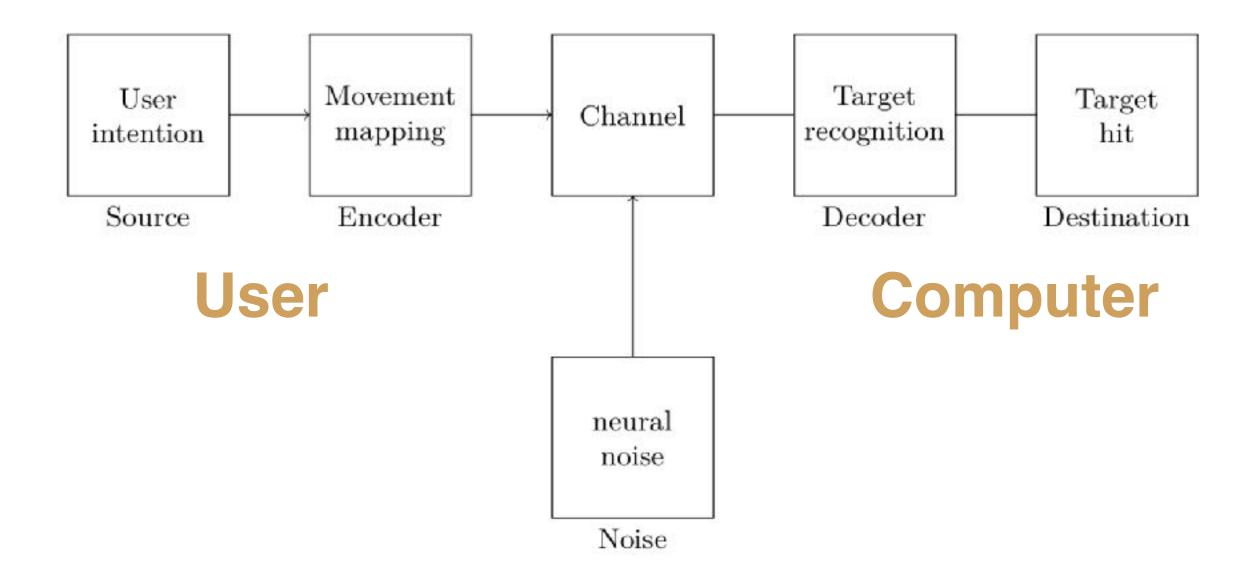








### Shannon meets Fitts



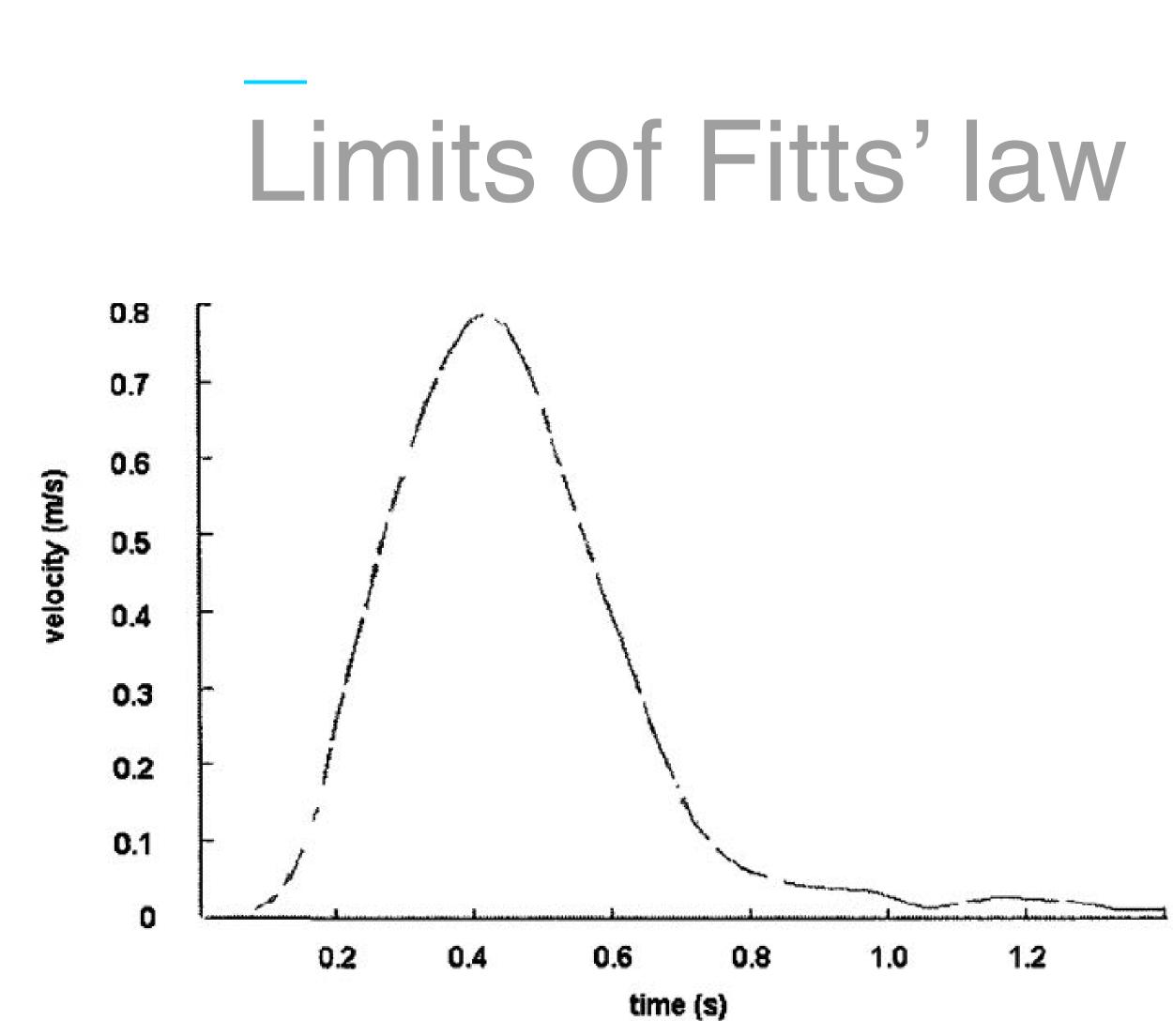
Gori, Rioul & Guiard, 2018

#### Modeling the motor system as the (noisy) channel

If e is the error rate

 $\begin{pmatrix} D \\ 1 + - \\ W \end{pmatrix}$  $C = (1 - e)\log_2$ 





First, ballistic movement, followed by corrective movements

Validity of the law Distance < amplitude of the arm Target size > motor tremor

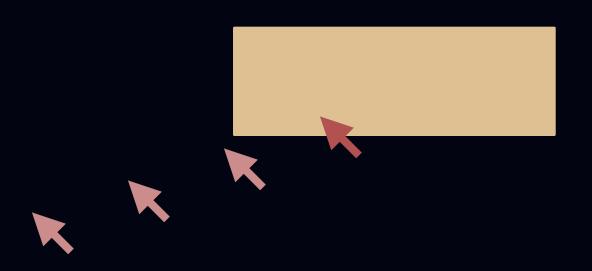
Distance < ~1m Target size > ~0.5mm **ID** < ~11 bits



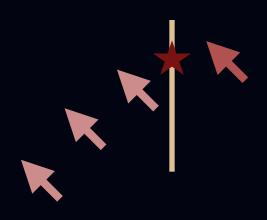


### Other laws of movement

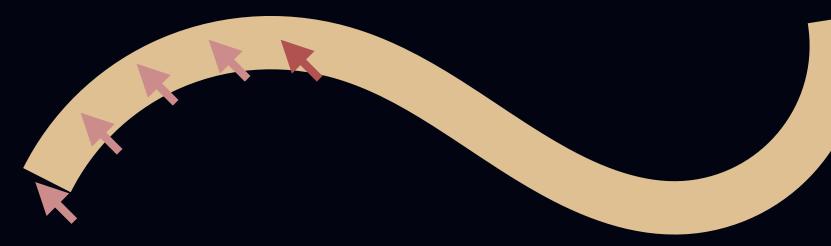
#### Fitts' law in 2D



#### Goal passing / crossing (Accot & Zhai)



#### The Steering law (Accot)











### "Beating" Fitts' Law

#### How can the system help the user reach the target faster?

Pointing as human-computer partnership



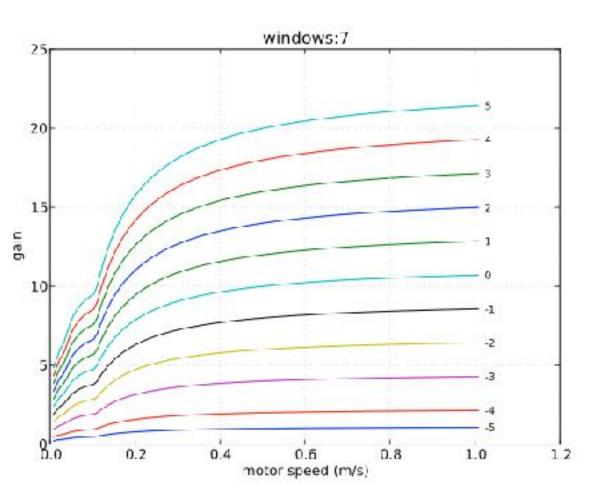
### "Beating" Fitts' Law

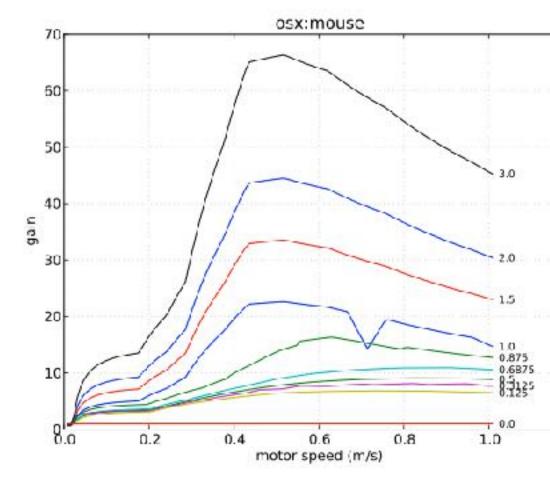
#### How can the system help the user reach the target faster?

1. Extract user intention



### Pointer acceleration Transfer function





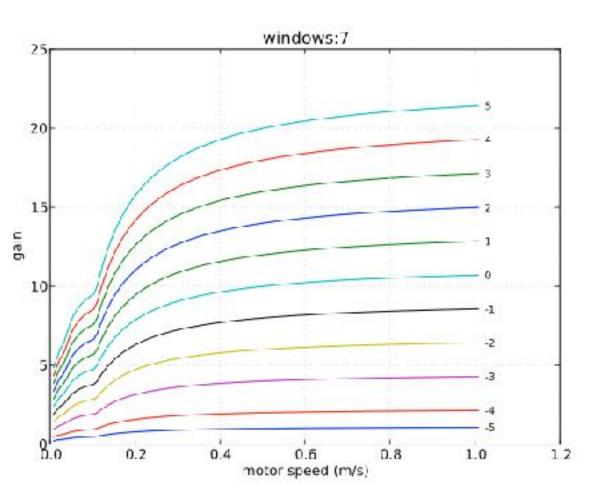
#### Move the cursor proportionally faster when the mouse moves faster: moving fast means wanting to go further away

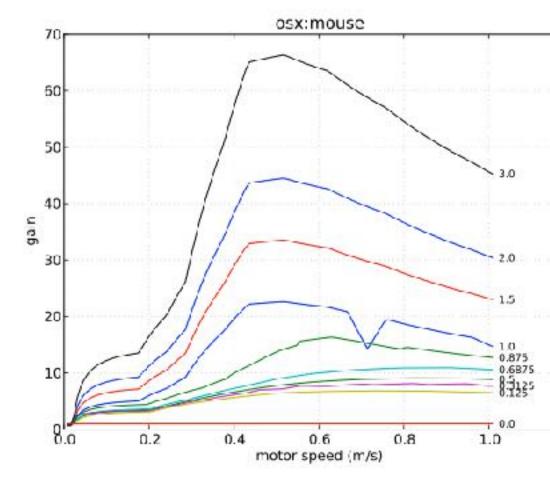
Casiez et al., 2008

1.2

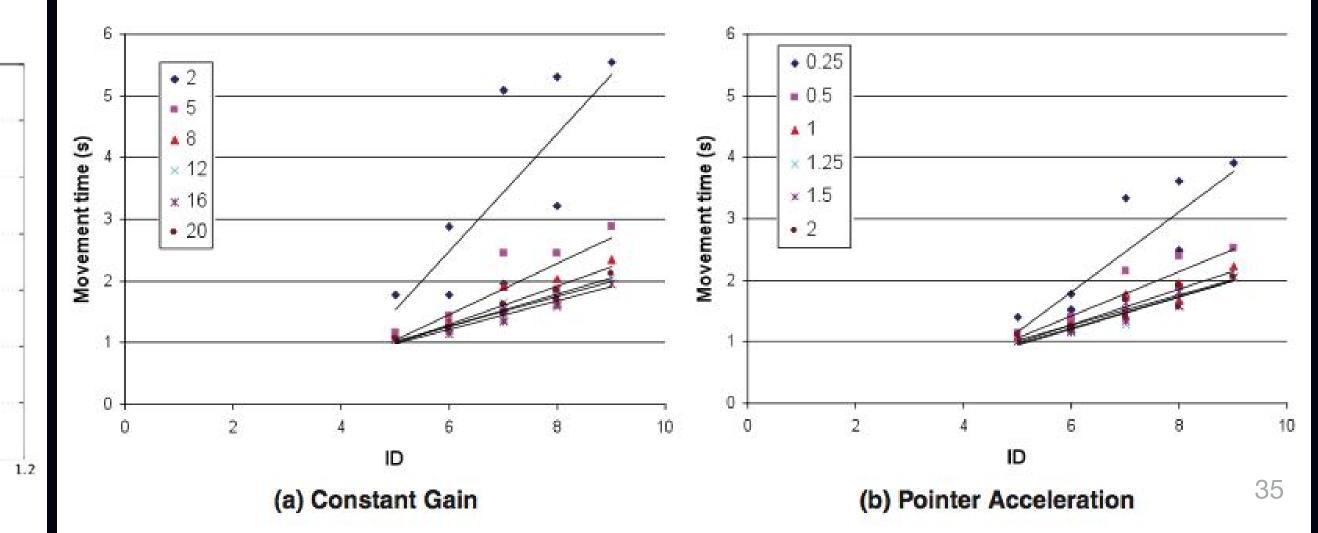


### Pointer acceleration Transfer function





#### Real but moderate effect on performance



### Gliding cursor



#### Beaudouin-Lafon et al., 2014

#### Cursor with inertia

#### Similar to scrolling a list on a smartphone

Does not improve pointing time BUT user controls the cursor only part of the time



## "Beating" Fitts' Law

### How can the system help the user reach the target faster?

Extract user intention
 Use information about targets



# Semantic pointing

Blanch et al., 2004

Adapt the transfer function to the "landscape" of targets: higher gain in the space between targets



# Semantic pointing

	Alert Dialog
	There are unsaved changes What would you like to do?
Don't	Save Cancel Save

#### Blanch et al., 2004

### Adapt the transfer function to the "landscape" of targets: higher gain in the space between targets

Visual space





# Semantic pointing



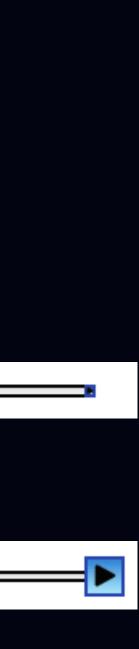
Blanch et al., 2004

### Adapt the transfer function to the "landscape" of targets: higher gain in the space between targets

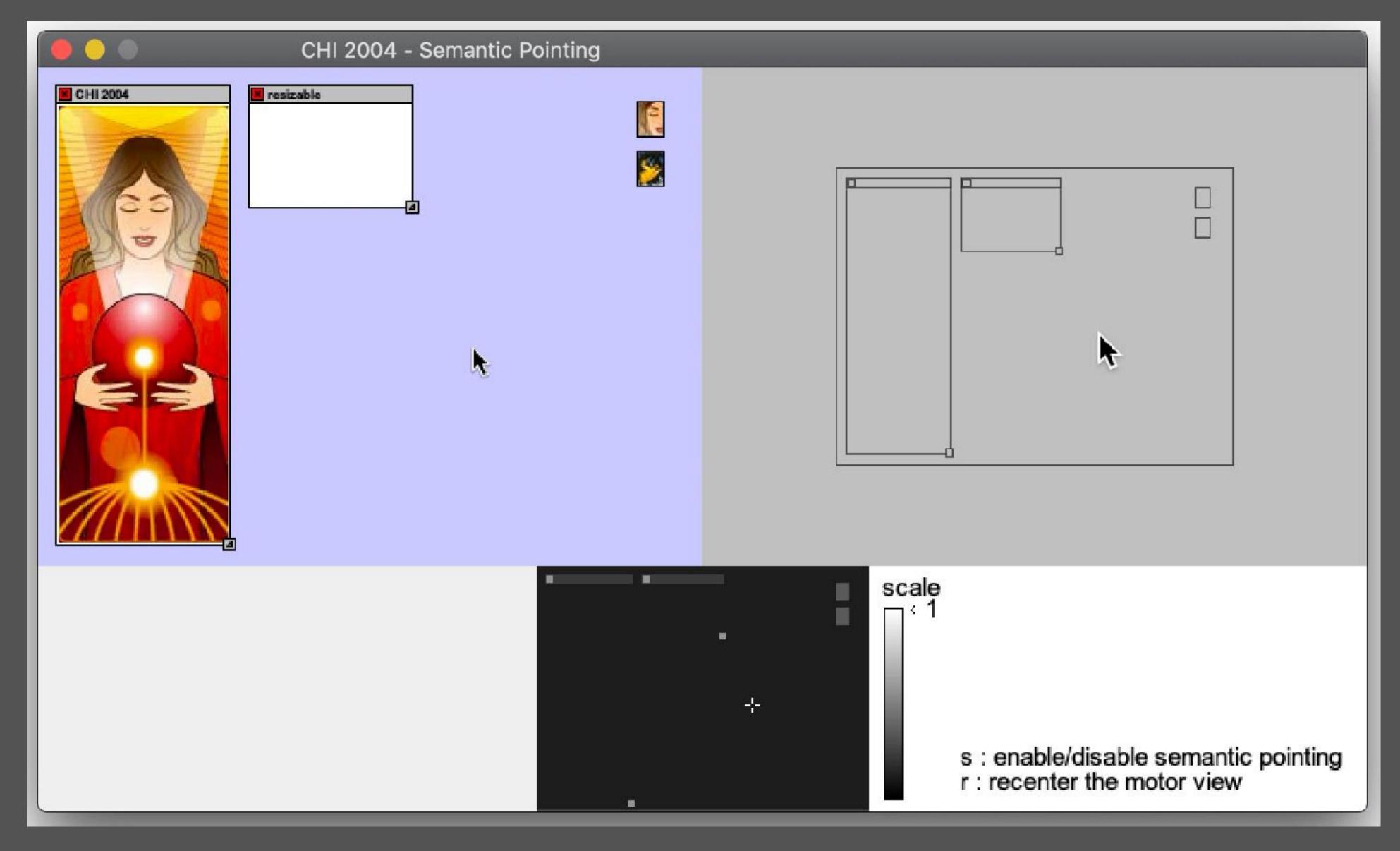
Visual space

vs. Motor space





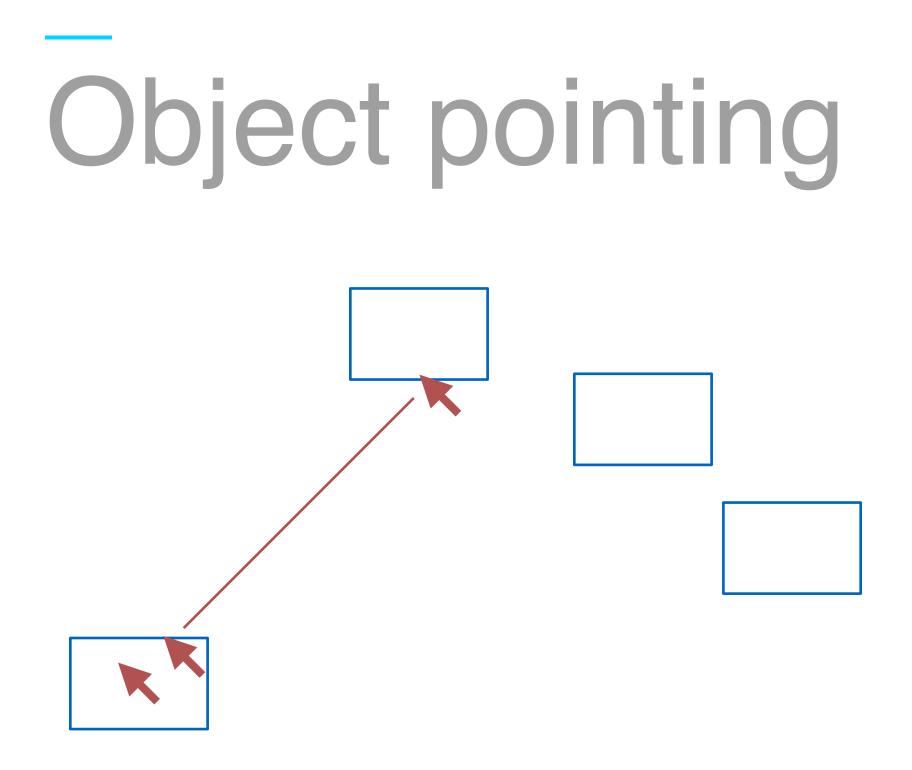




#### Semantic Pointing - Guiard, Blanch & Beaudouin-Lafon, 2004





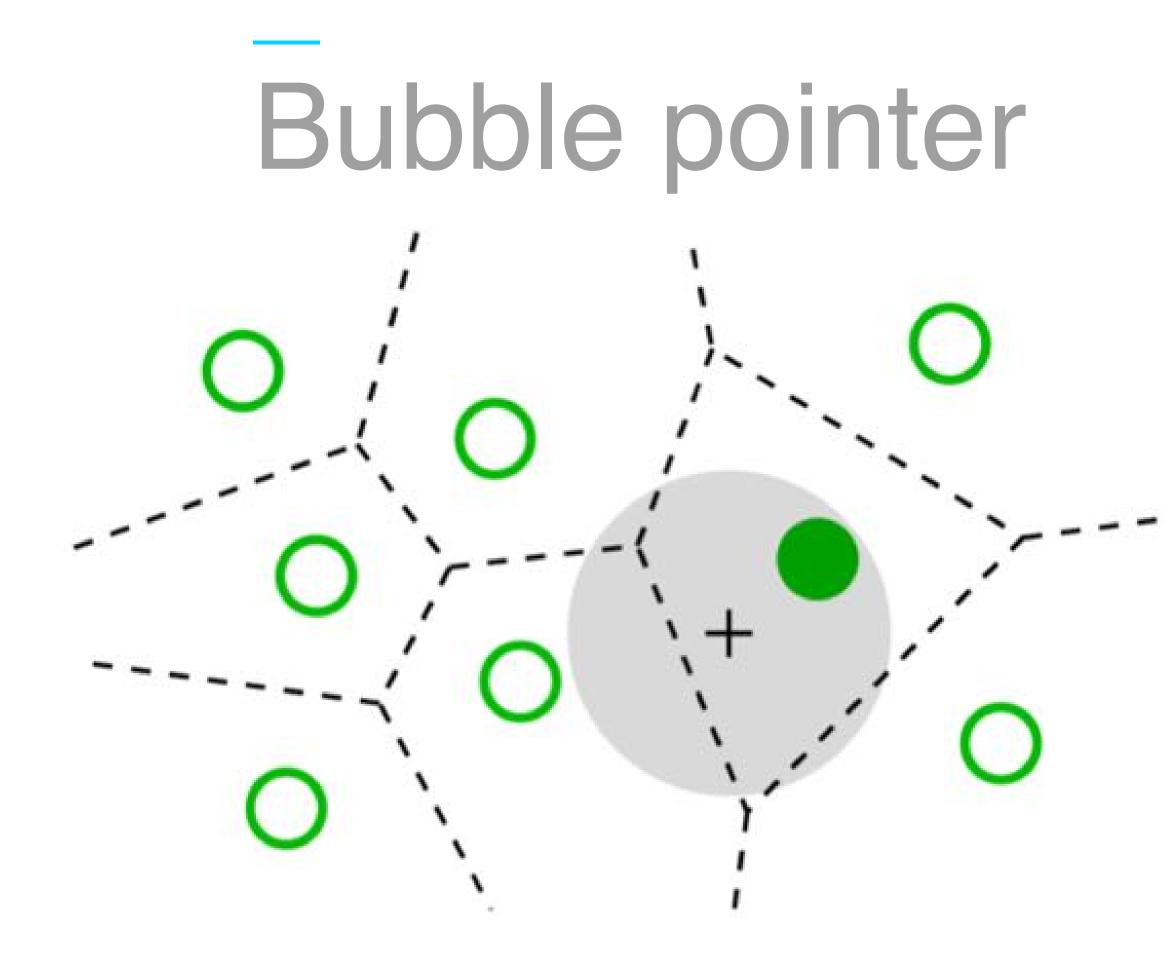


Guiard et al., 2004

Extreme version of Semantic Pointing: the cursor ignores empty space and jumps from one target to the next

Problem: error correction is costly





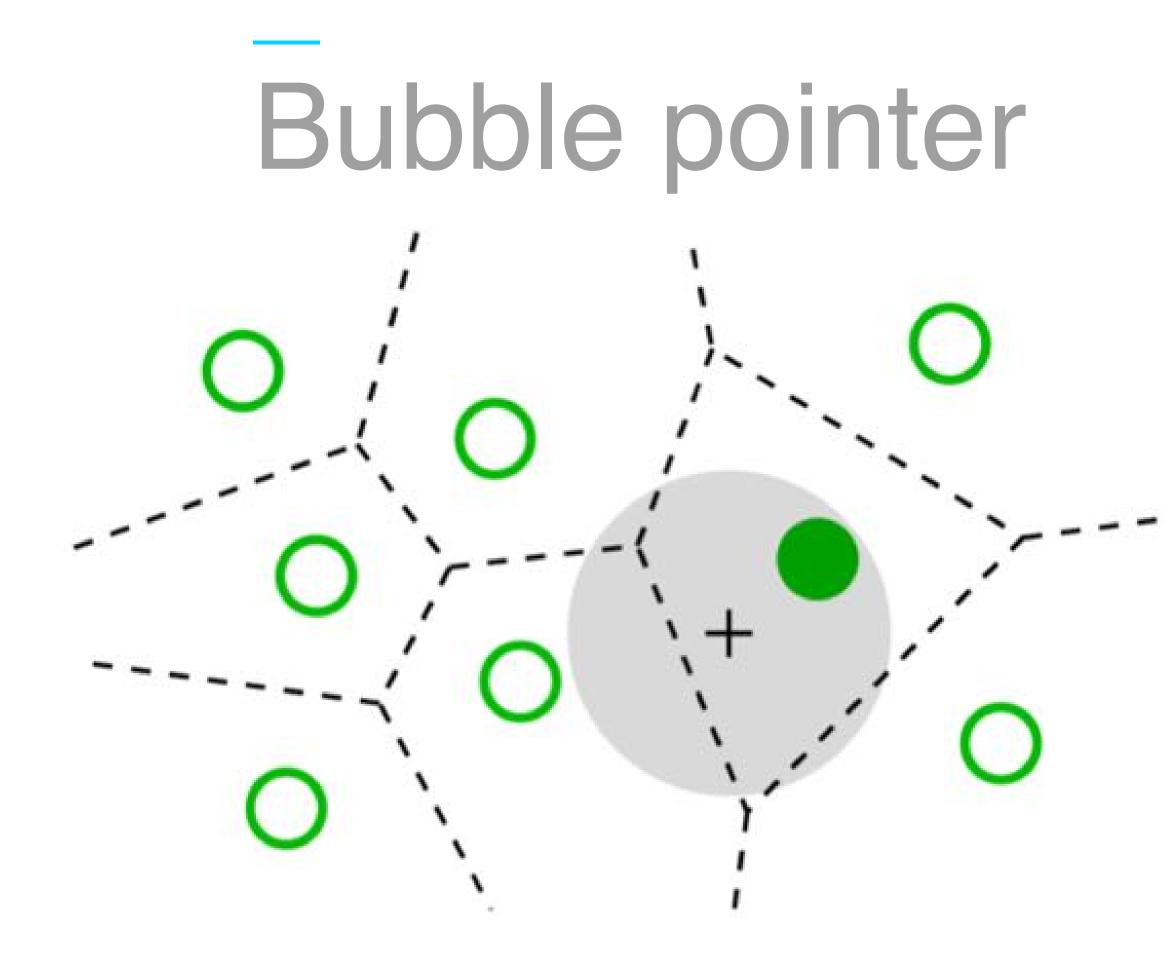
Grossman & Balakrishnan, 2005

Similar idea to Object Pointing: eliminate empty space

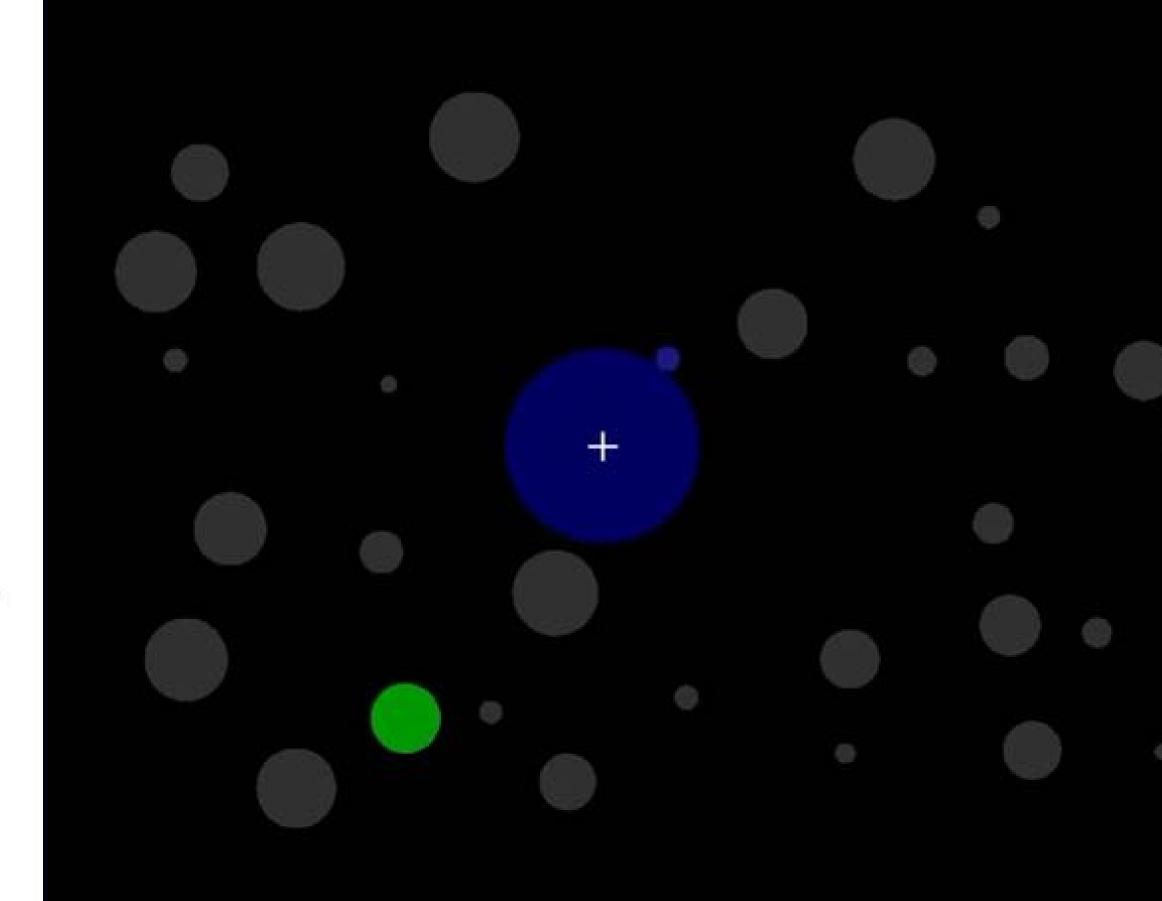
Any click is a click on the nearest target

Based on the Voronoi diagram of target positions: targets are effectively as big as possible





Grossman & Balakrishnan, 2005

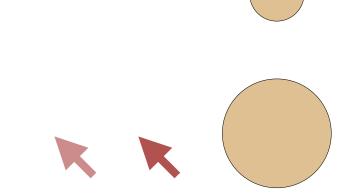




44

## Expanding targets





McGuffin & Balakrishnan, 2002 Zhai et al., 2003

Targets grow when close to cursor

Pointing time predicted by expanded target size



# Expanding targets



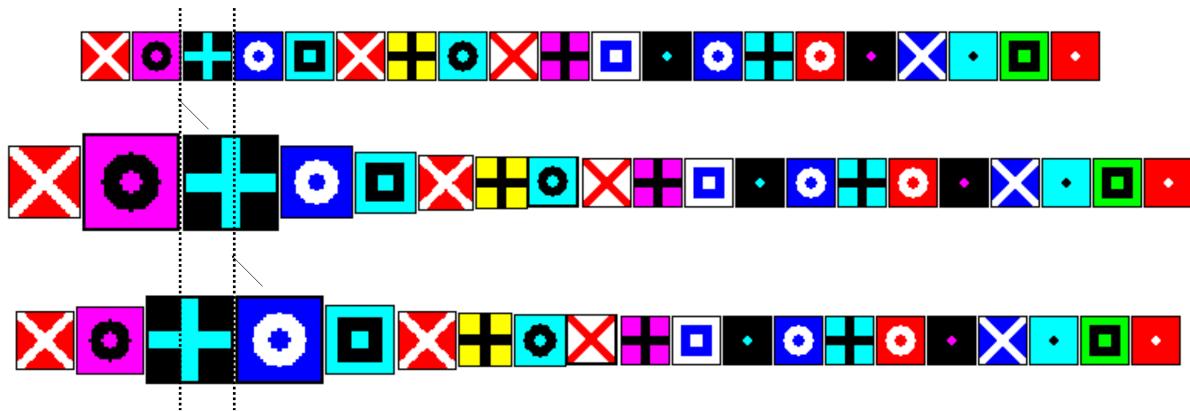
McGuffin & Balakrishnan, 2002 Zhai et al., 2003

Targets grow when close to cursor

Pointing time predicted by expanded target size



# Expanding targets



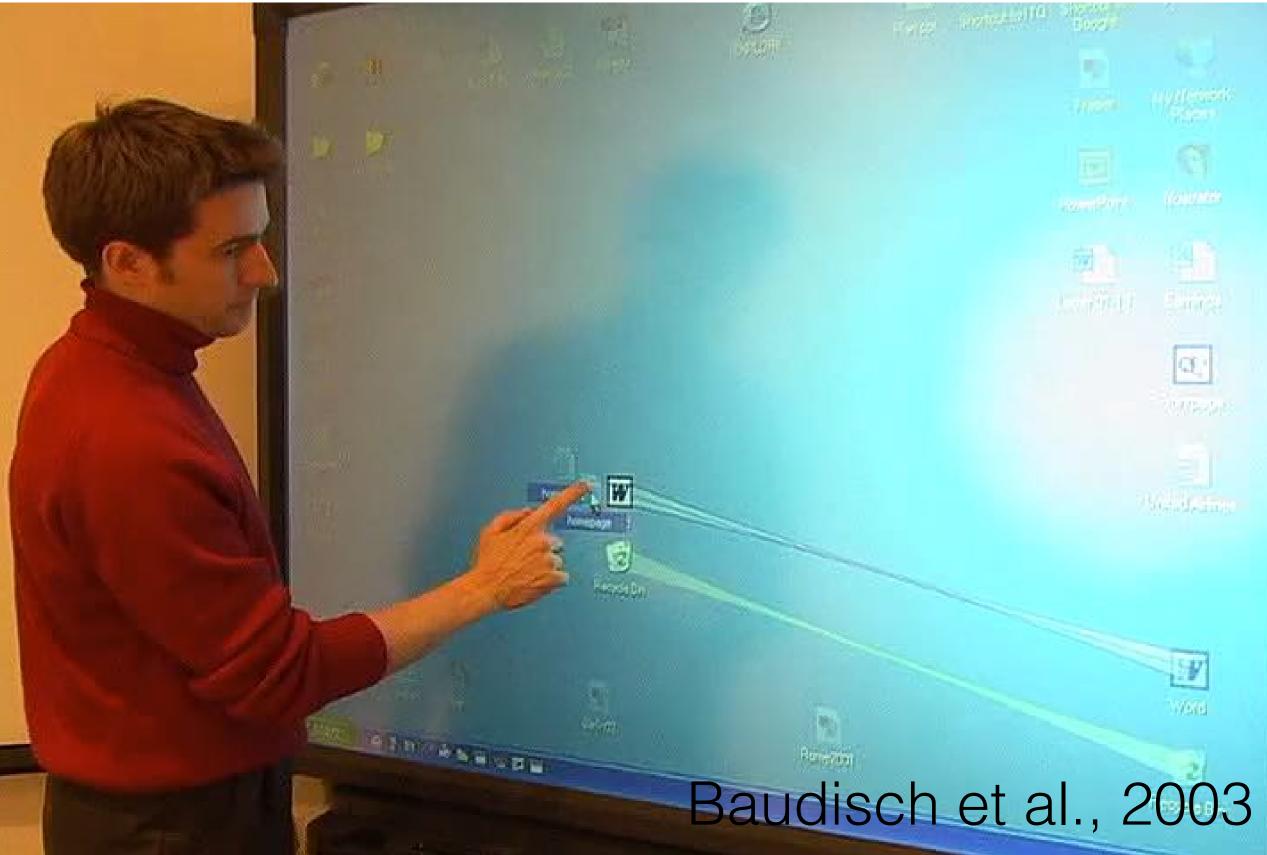
Targets grow when close to cursor

Pointing time predicted by expanded target size

But does not work with dense targets (example: MacOS dock)



### Drag-n-pop



### Reducing target distance during drag-and-drop by having target icons "fly" towards the cursor





## "Beating" Fitts' Law

### How can the system help the user reach the target faster?

Extract user intention
 Use information about targets
 Breaking the limits



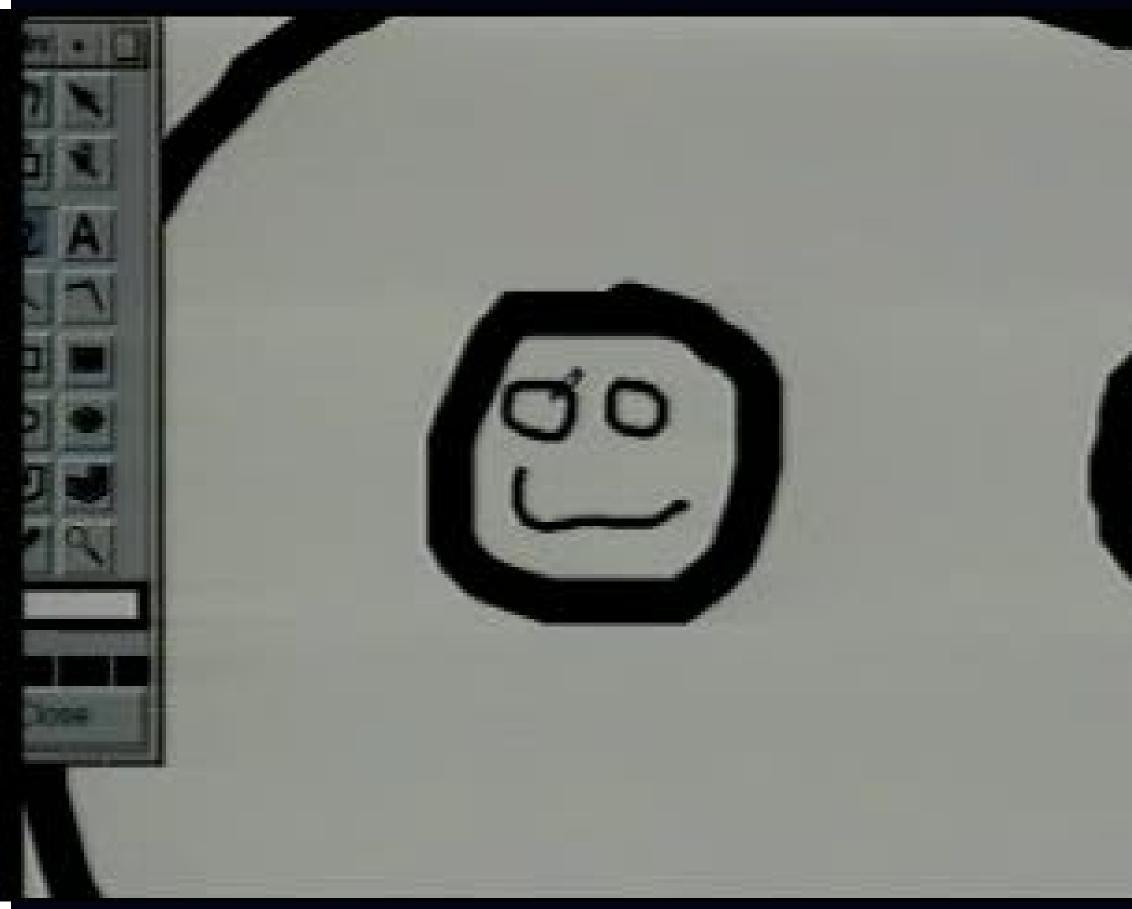
# Zoomable user interface (ZUI)



r Apr 1 Aug v Dec	*1992* Jan Eeb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
r Apr 1 Aug v Dec	*1997* Jan Eeb Mar Apr May Jun Jul Aug Sep Oct Nov Dec



#### Perlin & Fox, 1993

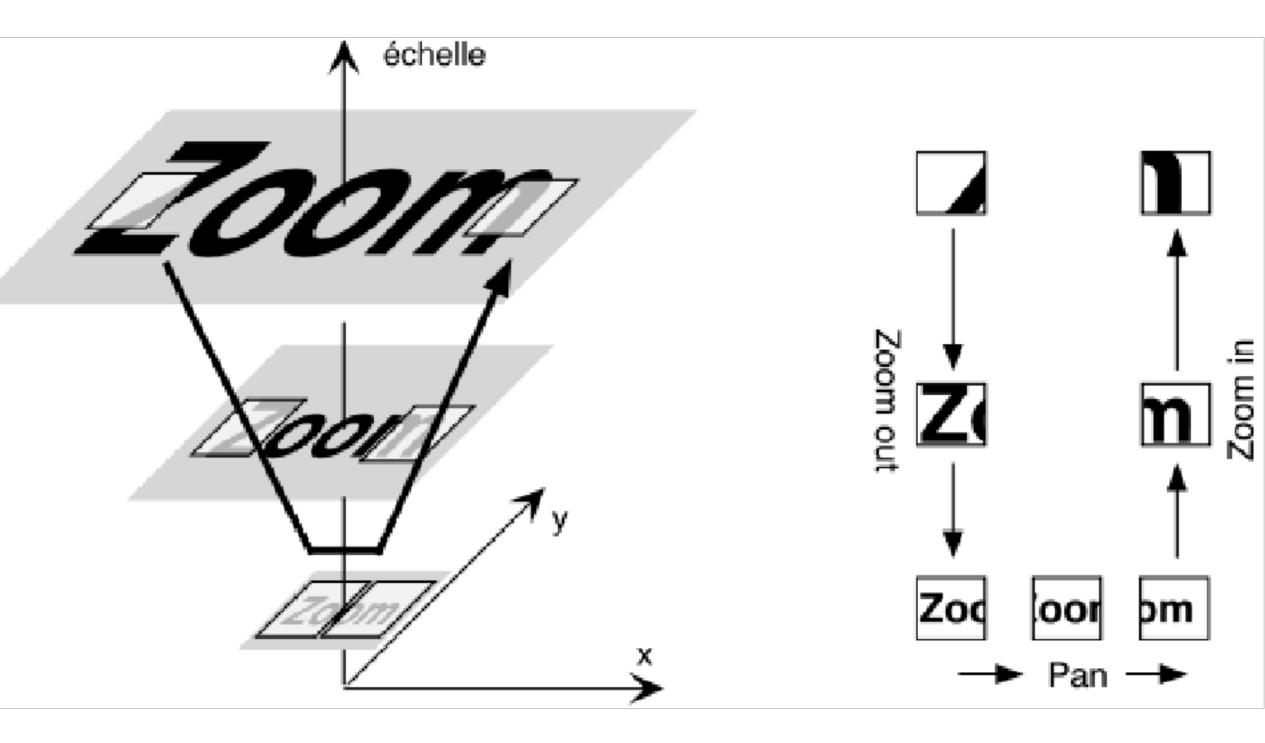


#### Bederson & Hollan, 1994





## Multiscale pointing

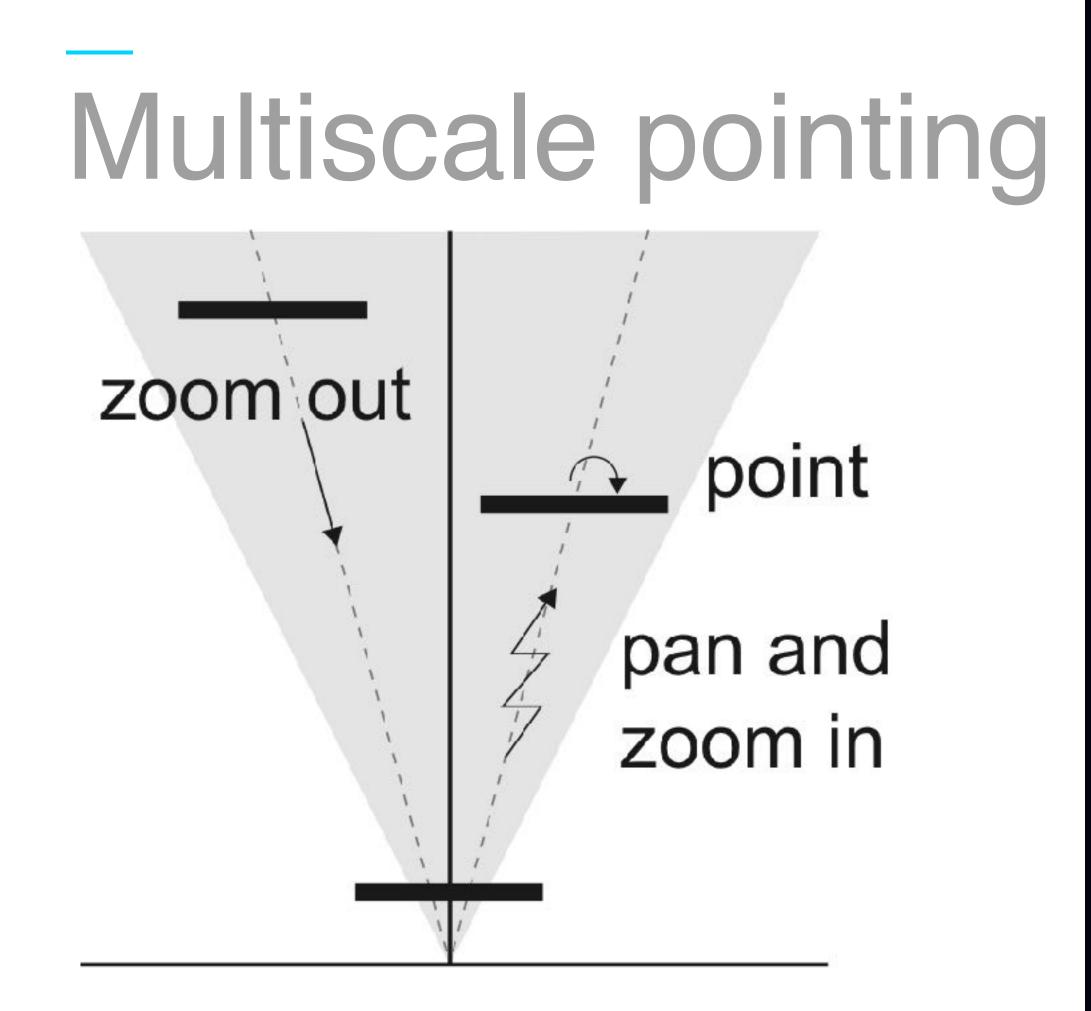


### Very different from "normal" pointing

### Zoom out to see the target Pan and zoom in towards it



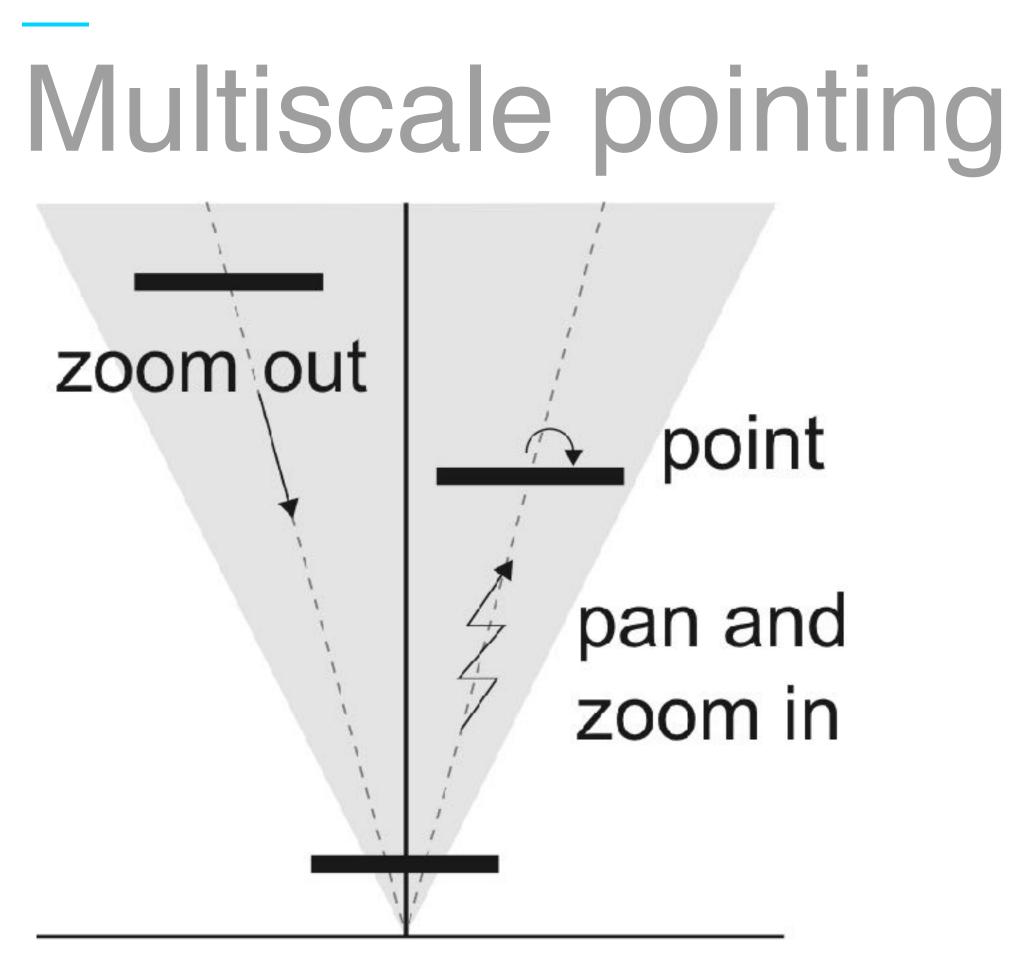
51



### Very different from "normal" pointing

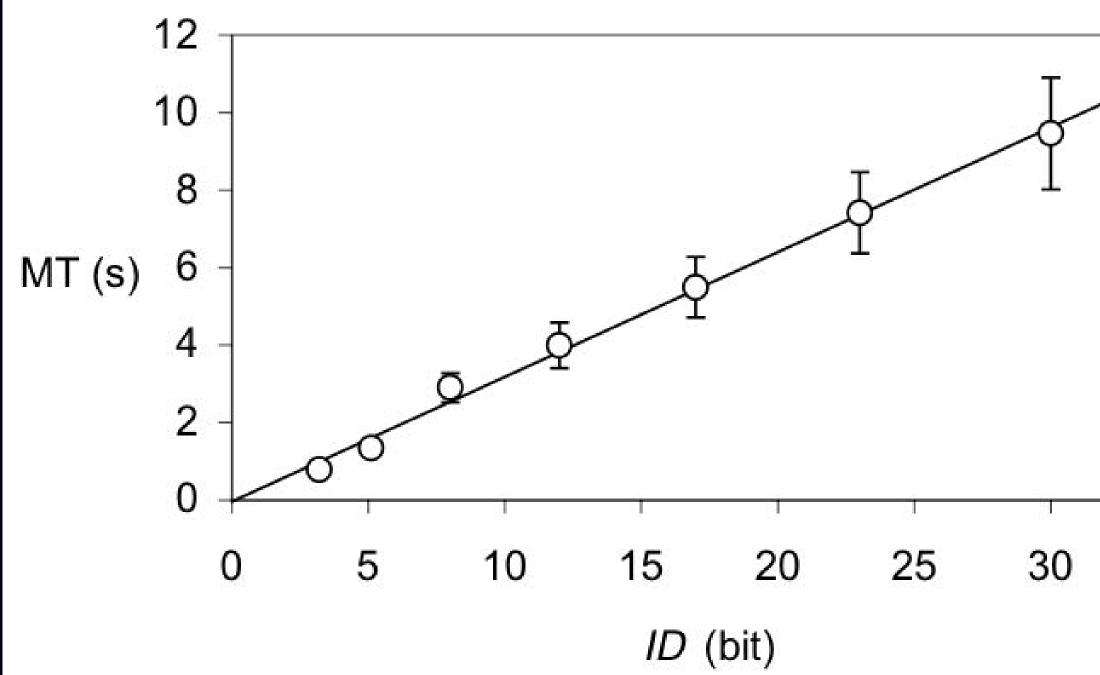
### Zoom out to see the target Pan and zoom in towards it

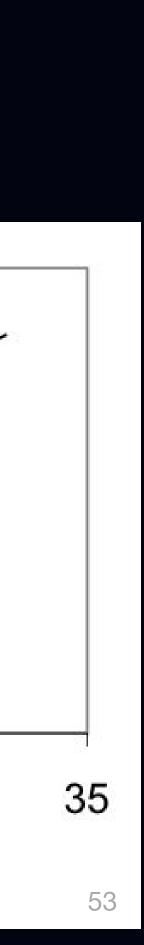


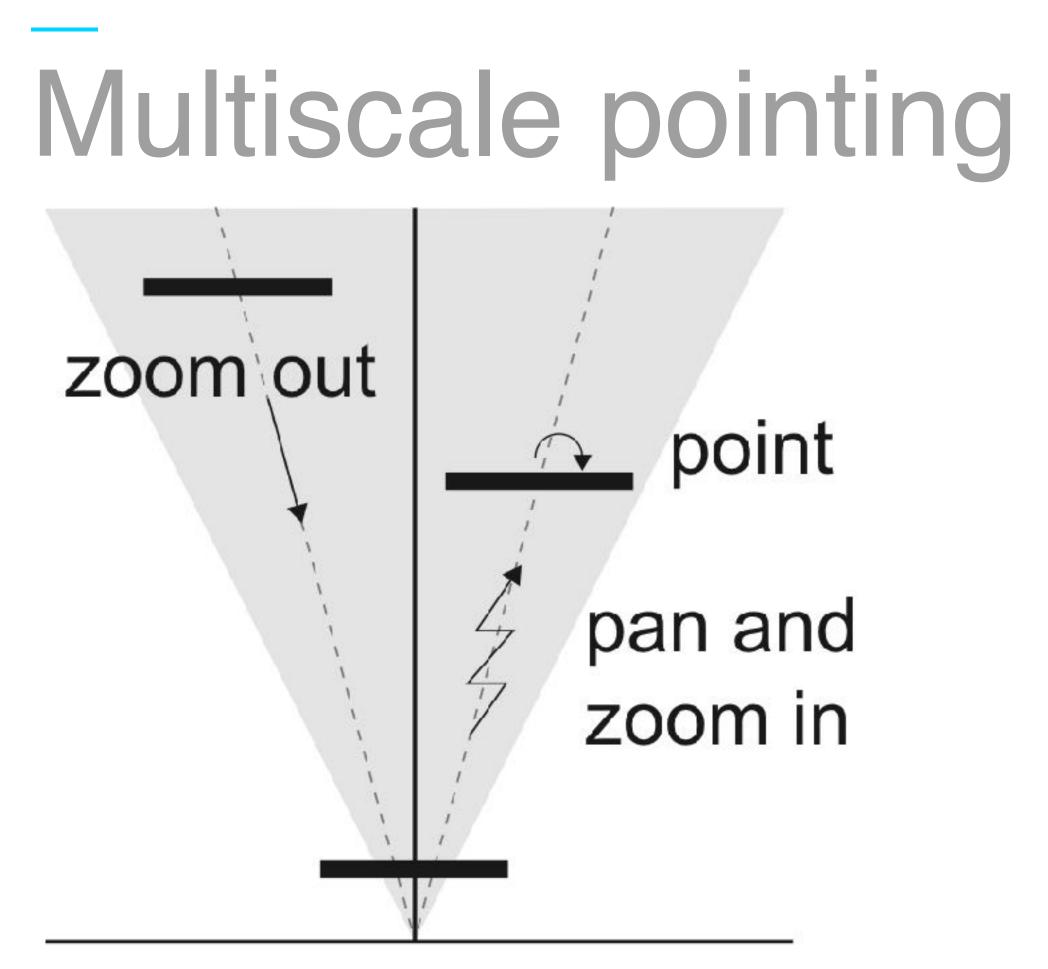


#### Guiard & Beaudouin-Lafon, 2004

### Pointing time predicted by Fitts' law up to ID = 30+

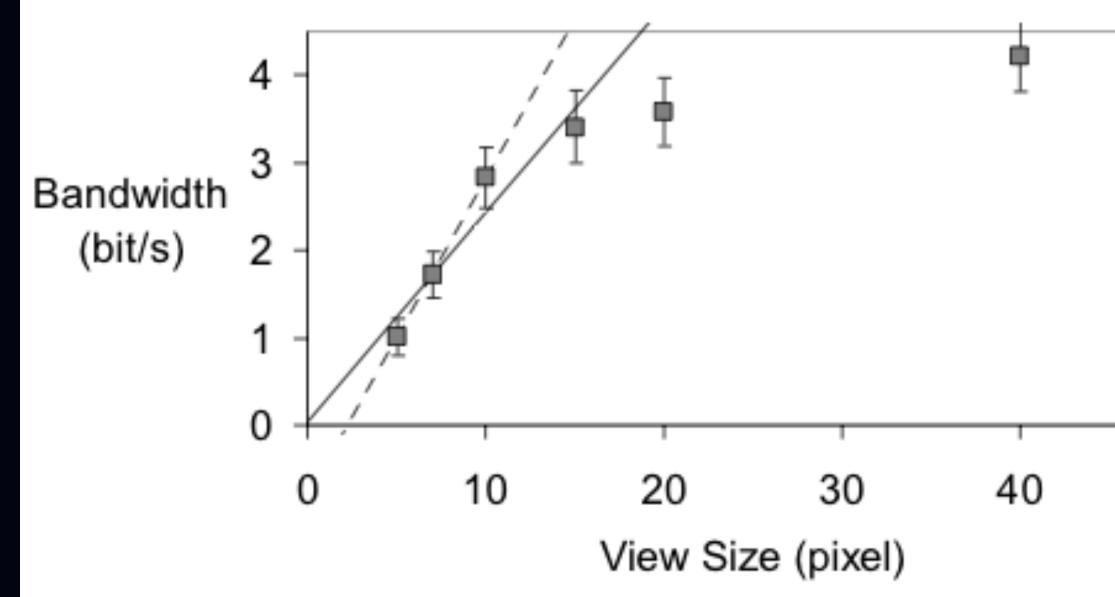






#### Guiard et al., 2004

### Effect of view size For small views: MT = k ID / V





### Orthozoom

222		And the Real Property lines	
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		SCENE III The same	4
		任然的本TRA's palace	45
		SCENE VI. New Minesses	51
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		POMPEY's galley, off	51
	ACT III	SCENE II. Rome Anante-	85
		COLEVER R3 Laberanchia	23
		SCENE IV Atless A room in SCENE 11/12 provide Amother	75
		OCTAVIUS CAESARybour	

(b)

Appert & Fekete, 2006

### Extend a scrollbar to pan and zoom a 1D document

Use orthogonal dimension to zoom

Twice as fast as the best known technique





### Orthozoom

222		And the Real Property lines	
ACT I	ICENE   Alexandria Arross		1.1
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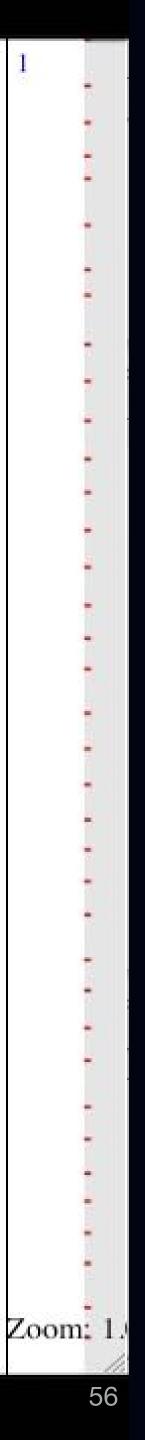
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		SCENE IV Atless A room in SCENE 11/12 provide Amother	75
		OCTAVIUS CAESARybour	

(b)

Appert & Fekete, 2006

#### The Tragedy of Antony and Cleopatra Dramatis Personae

MARK ANTONY OCTAVIUS CAESAR M. AEMILIUS LEPIDUS triumvirs. SEXTUS POMPEIUS DOMITIUS ENOBARBUS VENTIDIUS EROS SCARUS DERCETAS DEMETRIUS PHILO friends to Antony. MECAENAS AGRIPPA DOLABELLA PROCULEIUS THYREUS GALLUS MENAS friends to Caesar. MENECRATES VARRIUS friends to Pompey. TAURUS, lieutenant-general to Caesar. CANIDIUS, lieutenant-general to Antony. SILIUS, an officer in Ventidius's army. EUPHRONIUS, an ambassador from Antony to Caesar. ALEXAS MARDIAN, a Eunuch. SELEUCUS DIOMEDES attendants on Cleopatra. A Soothsayer. A Clown. CLEOPATRA, queen of Egypt. OCTAVIA, sister to Caesar and wife to Antony. CHARMIAN IRAS attendants on Cleopatra. Officers, Soldiers, Messengers, and other Attendants. SCENE In several parts of the Roman empire. ACT I



## "Beating" Fitts' Law

### How can the system help the user reach the target faster?

- 1. Extract user intention
- 2. Use information about targets
- 3. Breaking the limits
- 4. Challenge the user



Liu, D'Oliveira, Rioul, Beaudouin-Lafon, 2017



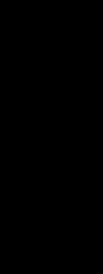
#### BIG: Bayesian Information Gain

#### (Bayesian Experimental Design + Information Theory)









59

#### \* **BIG: Bayesian Information Gain**

#### (Bayesian Experimental Design + Information Theory)

Prior knowledge  $P(\Theta = \theta)$ 



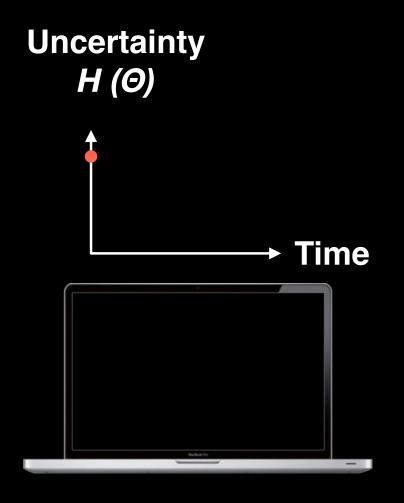






#### \* **BIG: Bayesian Information Gain**

(Bayesian Experimental Design + Information Theory)

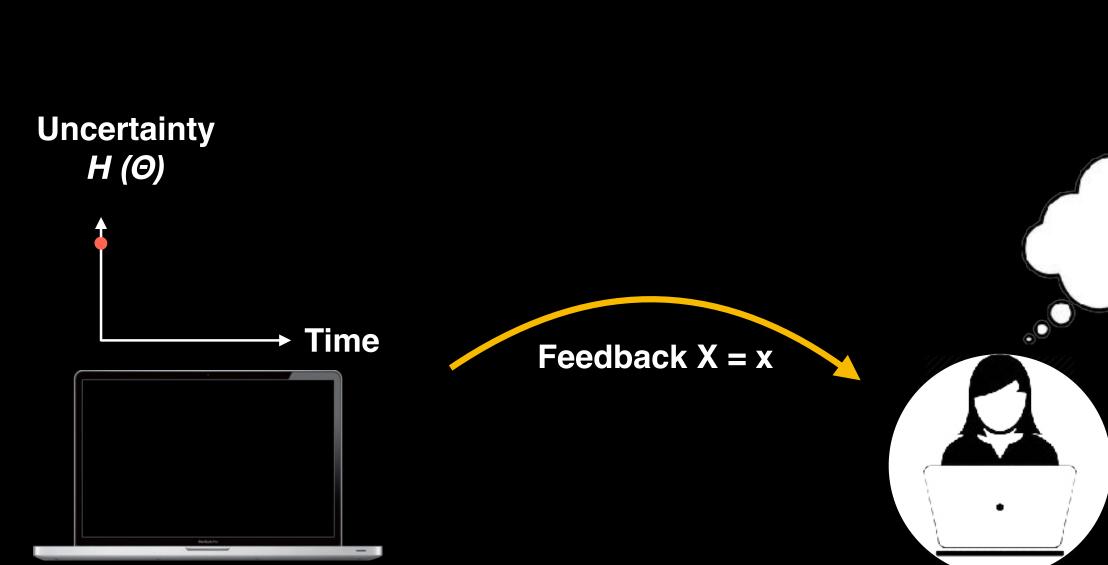






61

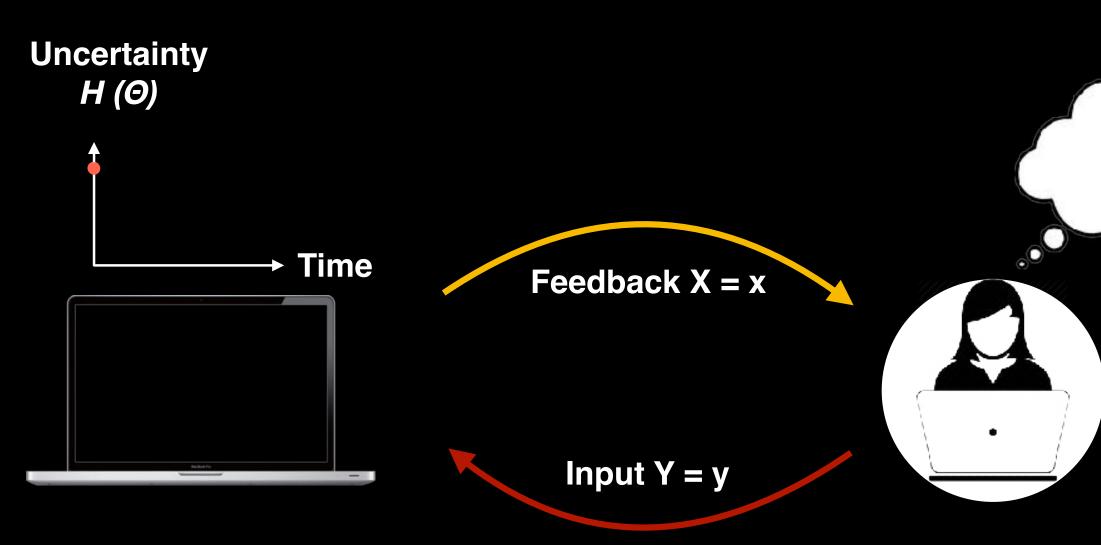
### BIG: Bayesian Information Gain (Bayesian Experimental Design + Information Theory)







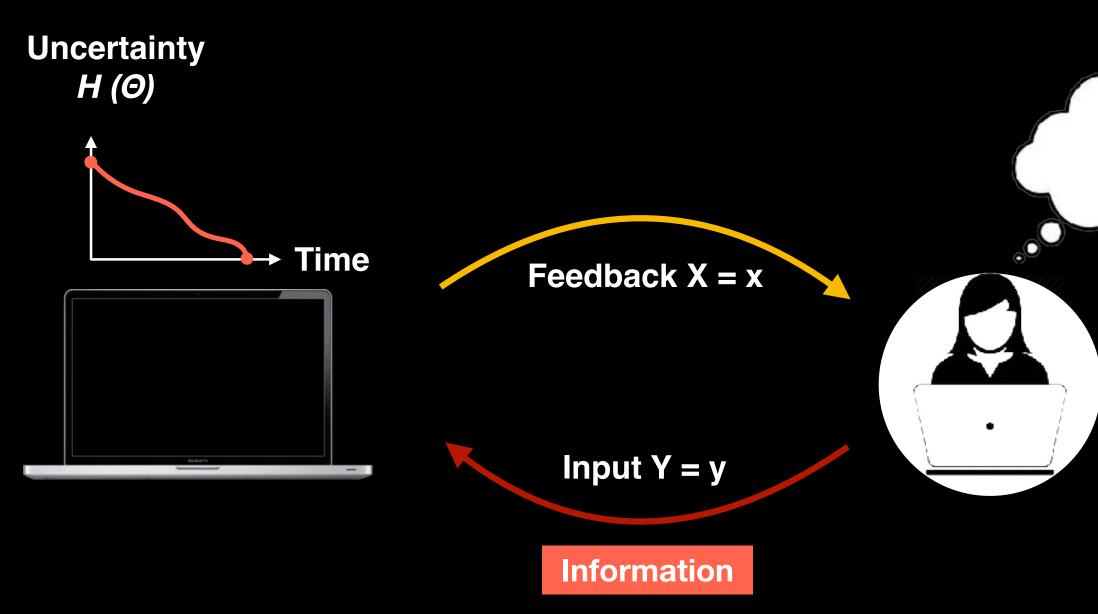
### BIG: Bayesian Information Gain (Bayesian Experimental Design + Information Theory)







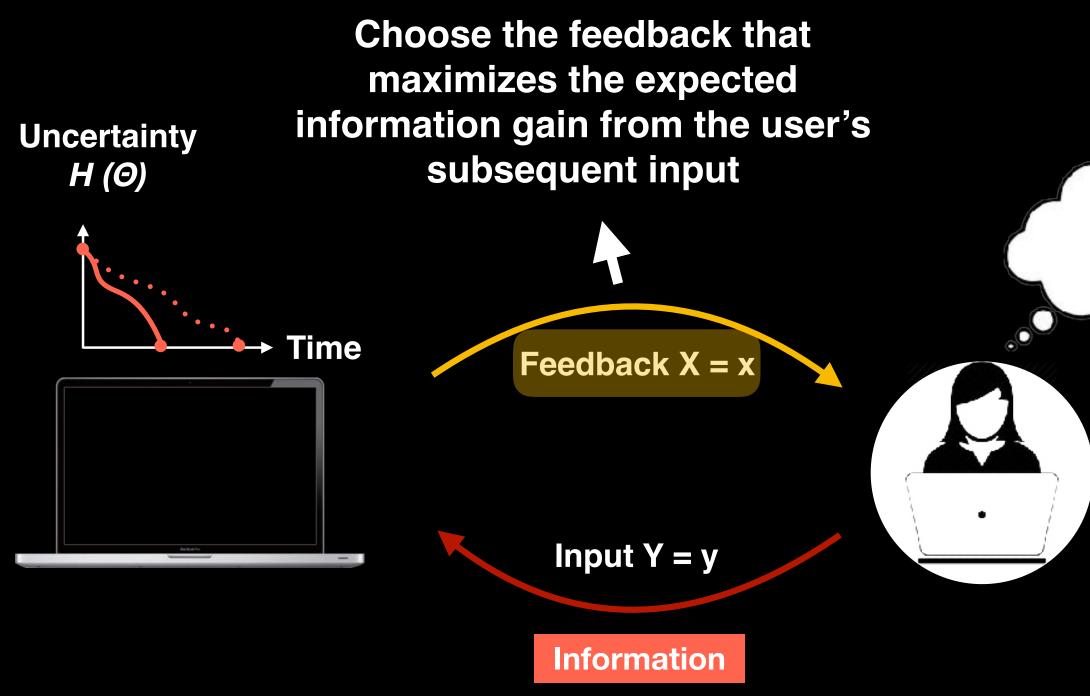
### BIG: Bayesian Information Gain (Bayesian Experimental Design + Information Theory)





64

#### BIG: Bayesian Information Gain (Bayesian Experimental Design + Information Theory)







#### **BIG: Bayesian Information Gain** (Bayesian Experimental Design + Information Theory)

The computer's Uncertainty about the user's goal

$$H(\Theta) = -\sum_{i=1}^{n}$$

The computer's updated knowledge about the user's goal

$$P(\Theta = \theta | X = x, Y = y) =$$

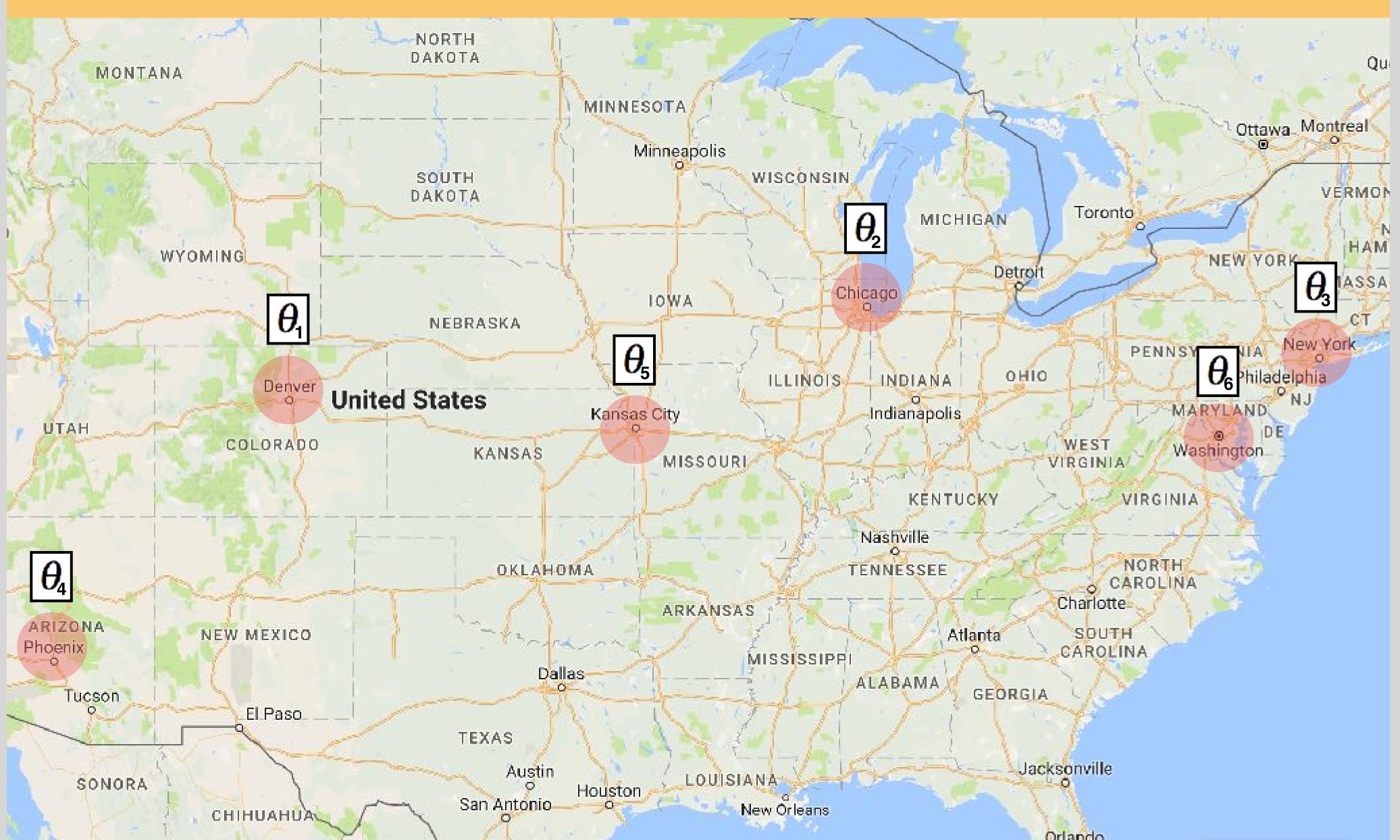
• The information gained by the computer from the user's input

$$IG(\Theta|X=x,Y=y)=H(\Theta)-H(\Theta|X=x,Y=y)$$

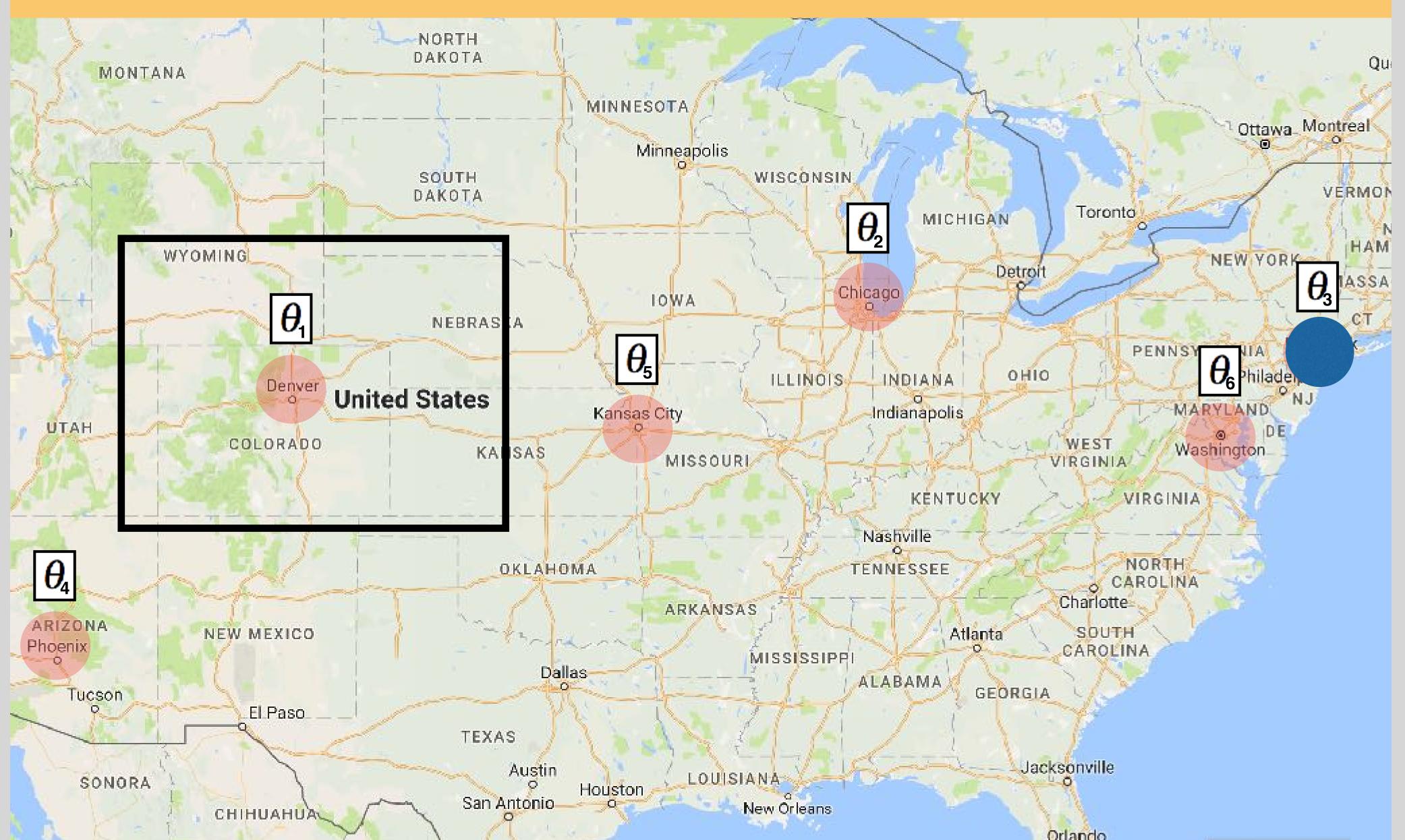
$$P(\Theta = \theta_i) \log_2 P(\Theta = \theta_i)$$

$$\frac{P(Y = y | \Theta = \theta, X = x)P(\Theta = \theta)}{P(Y = y | X = x)}$$











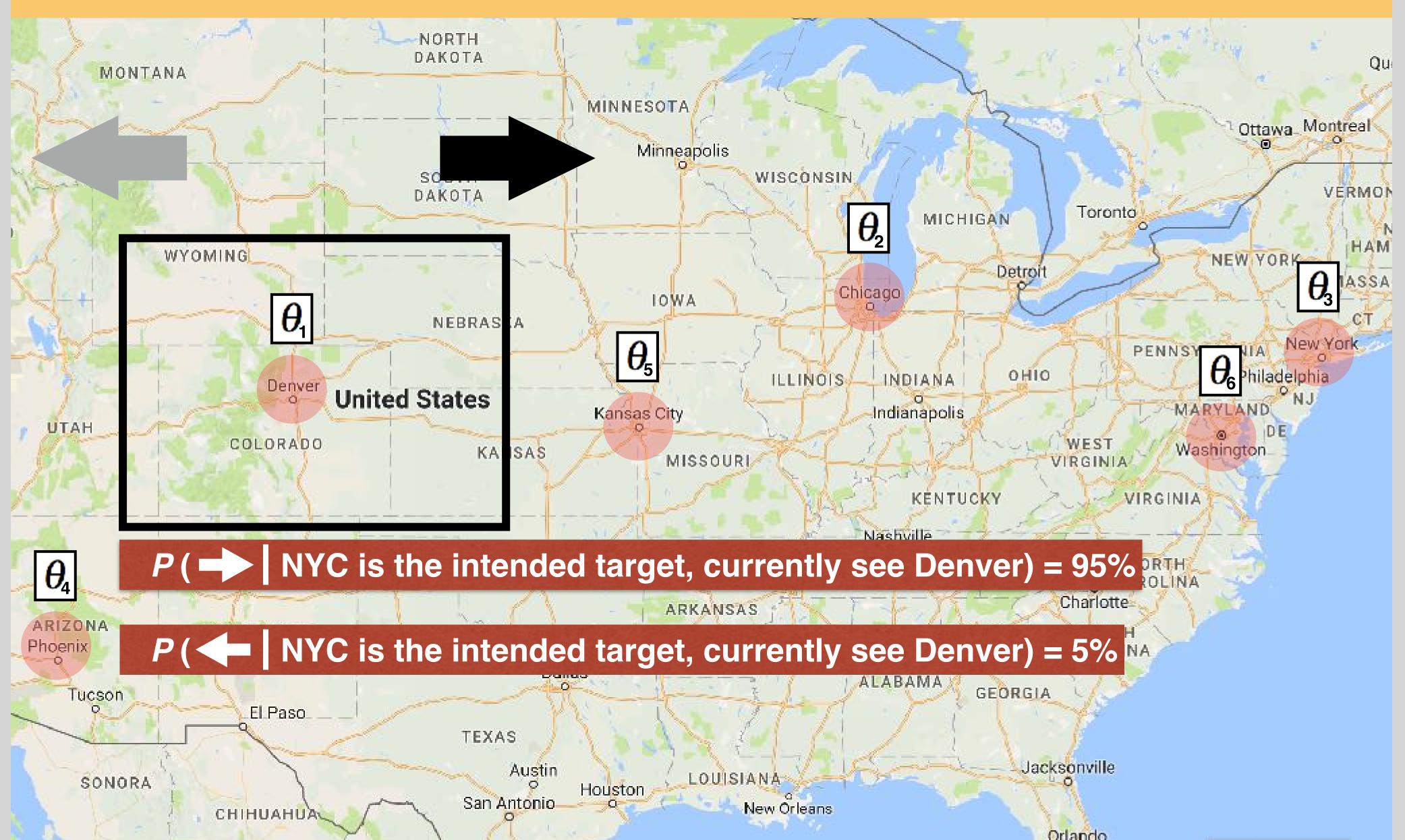
### User actions:

8 pan directions
1 zoom-in region











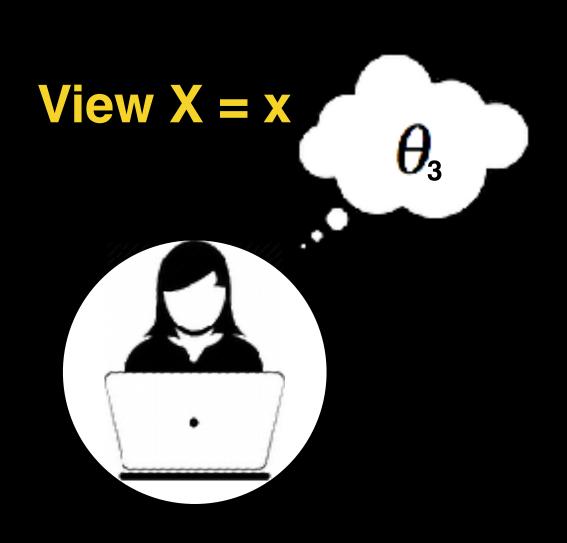
$$P(\Theta = \theta | X = x, Y = y)$$

#### Update its knowledge



$$P(\Theta = \theta_i)$$

User Input Y = y



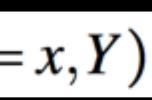
#### $IG(\Theta|X=x,Y) = H(\Theta) - H(\Theta|X=x,Y)$

Navigate to a new view that maximizes the expected information gain



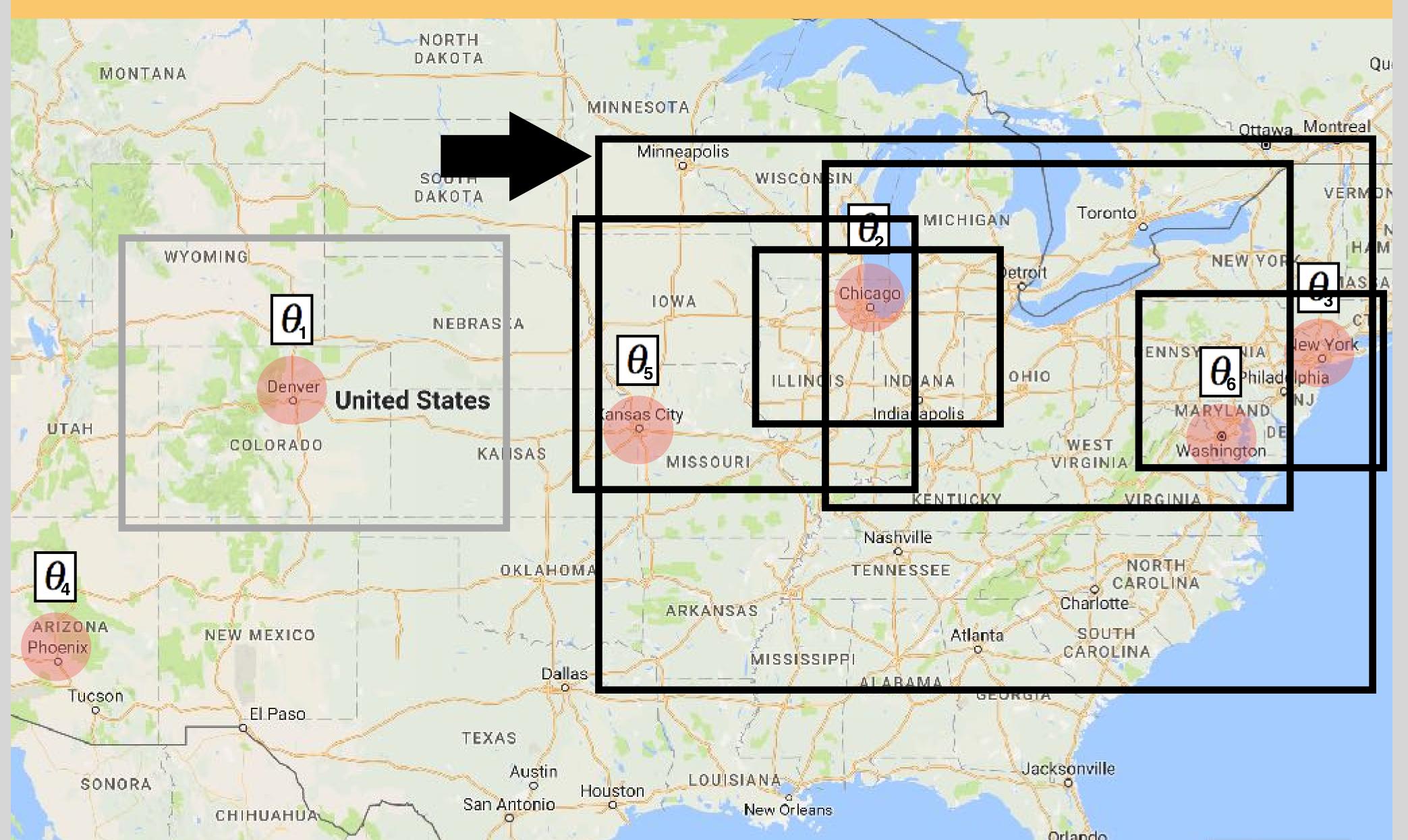
$$P(\Theta = \theta)$$

User Input Y = y

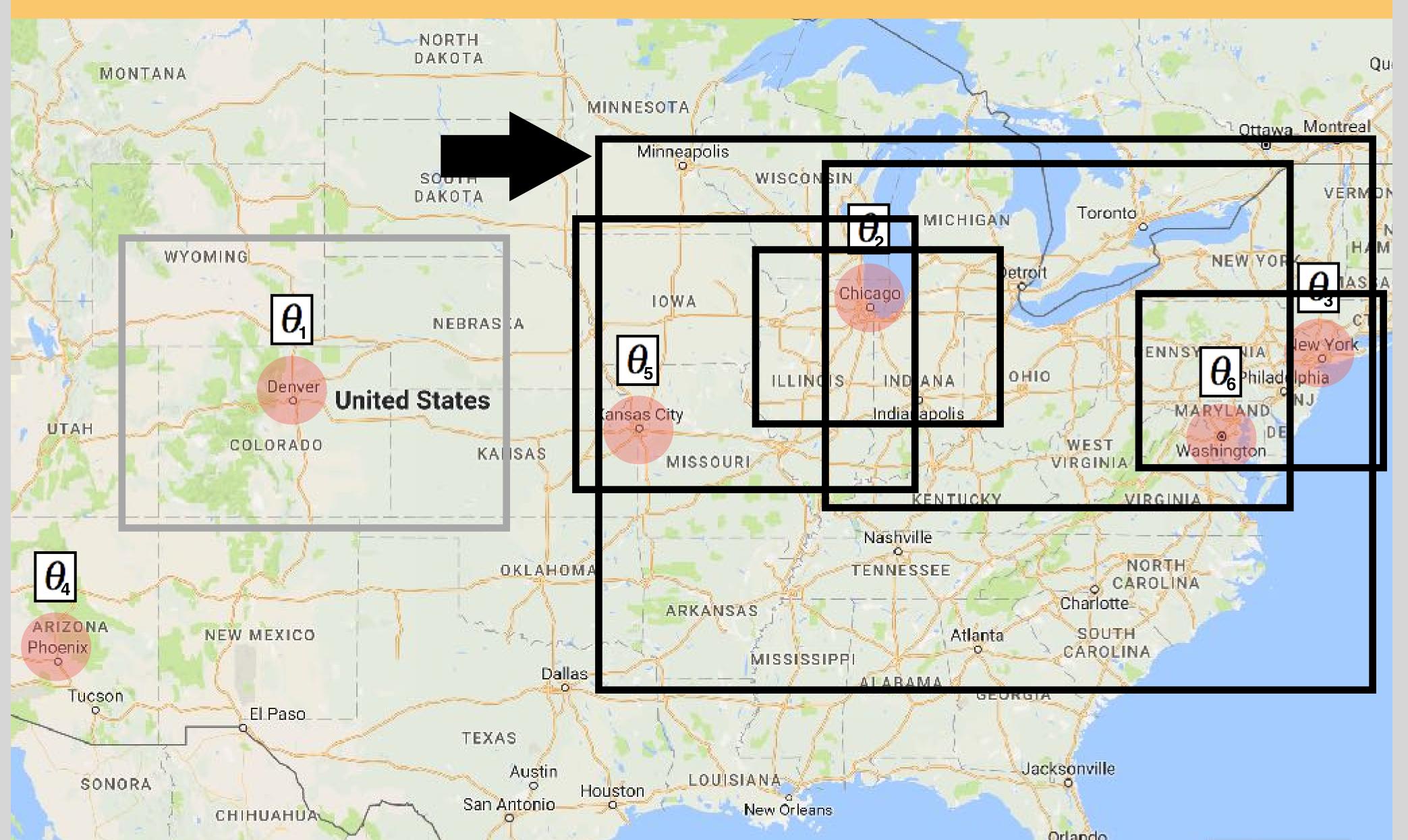




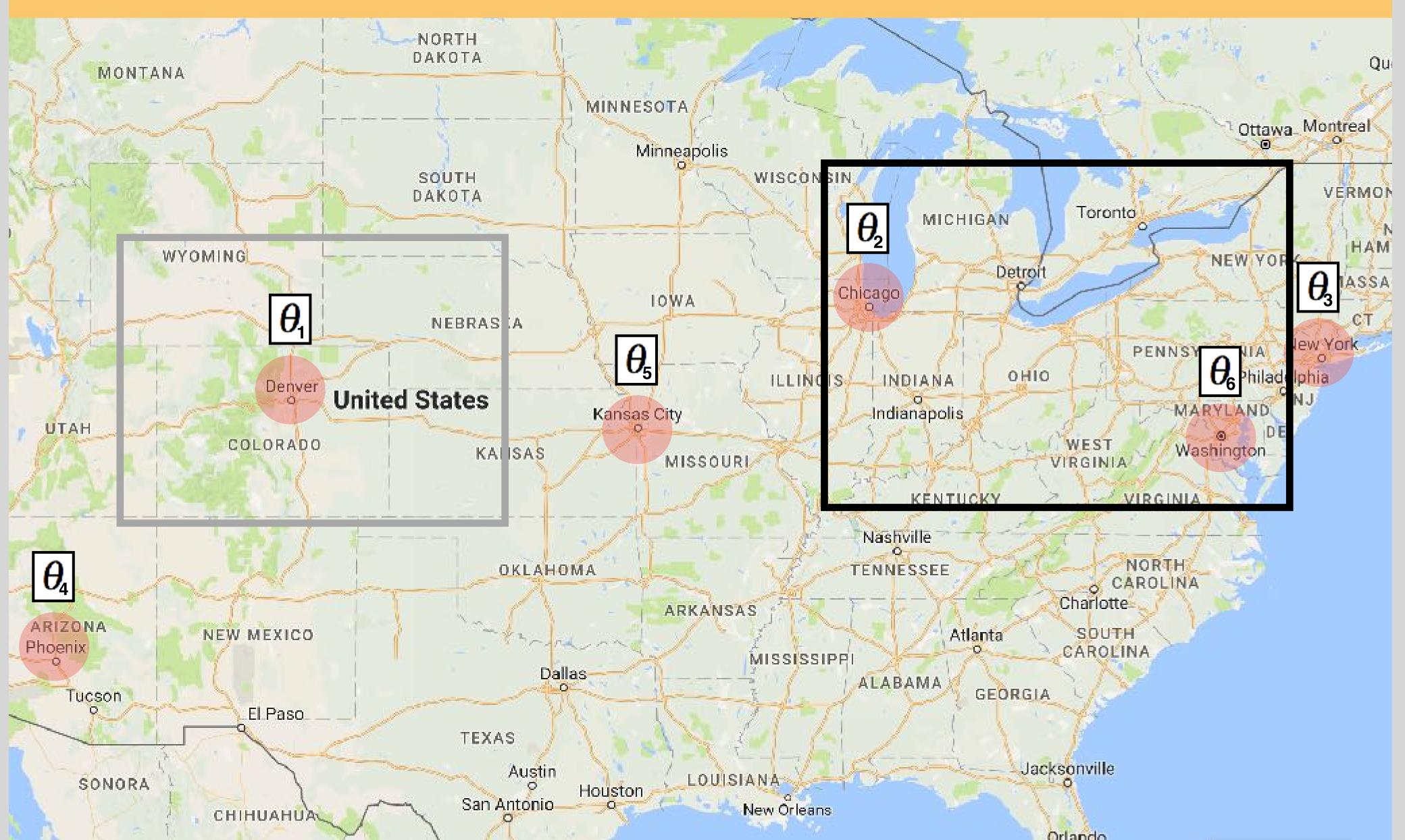
72













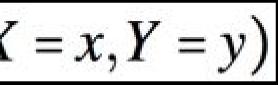
#### $IG(\Theta|X=x,Y=y)=H(\Theta)-H(\Theta|X=x,Y=y)$

#### **Calculate the actual** information gain



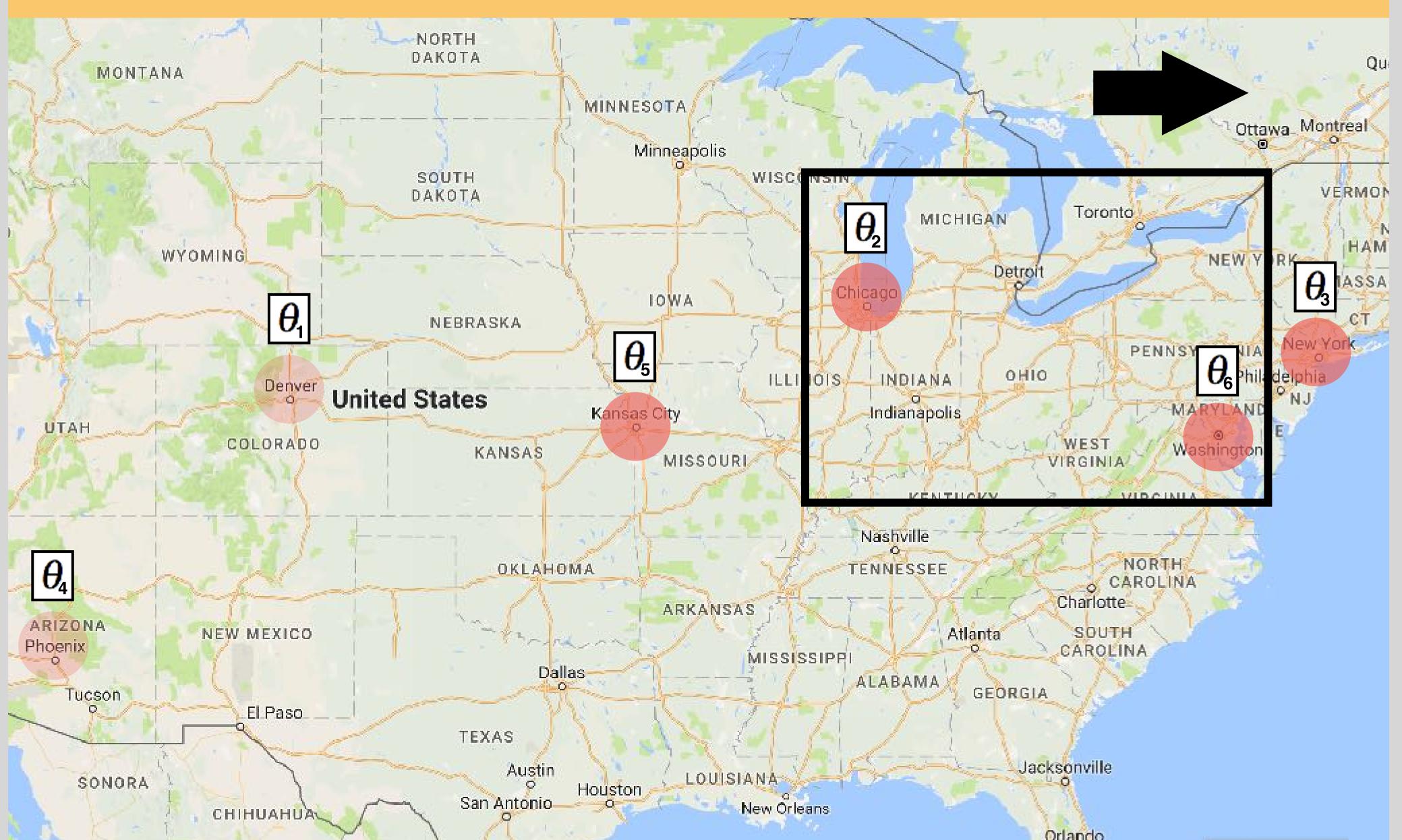
$$P(\Theta = \theta_i)$$

User Input Y = y













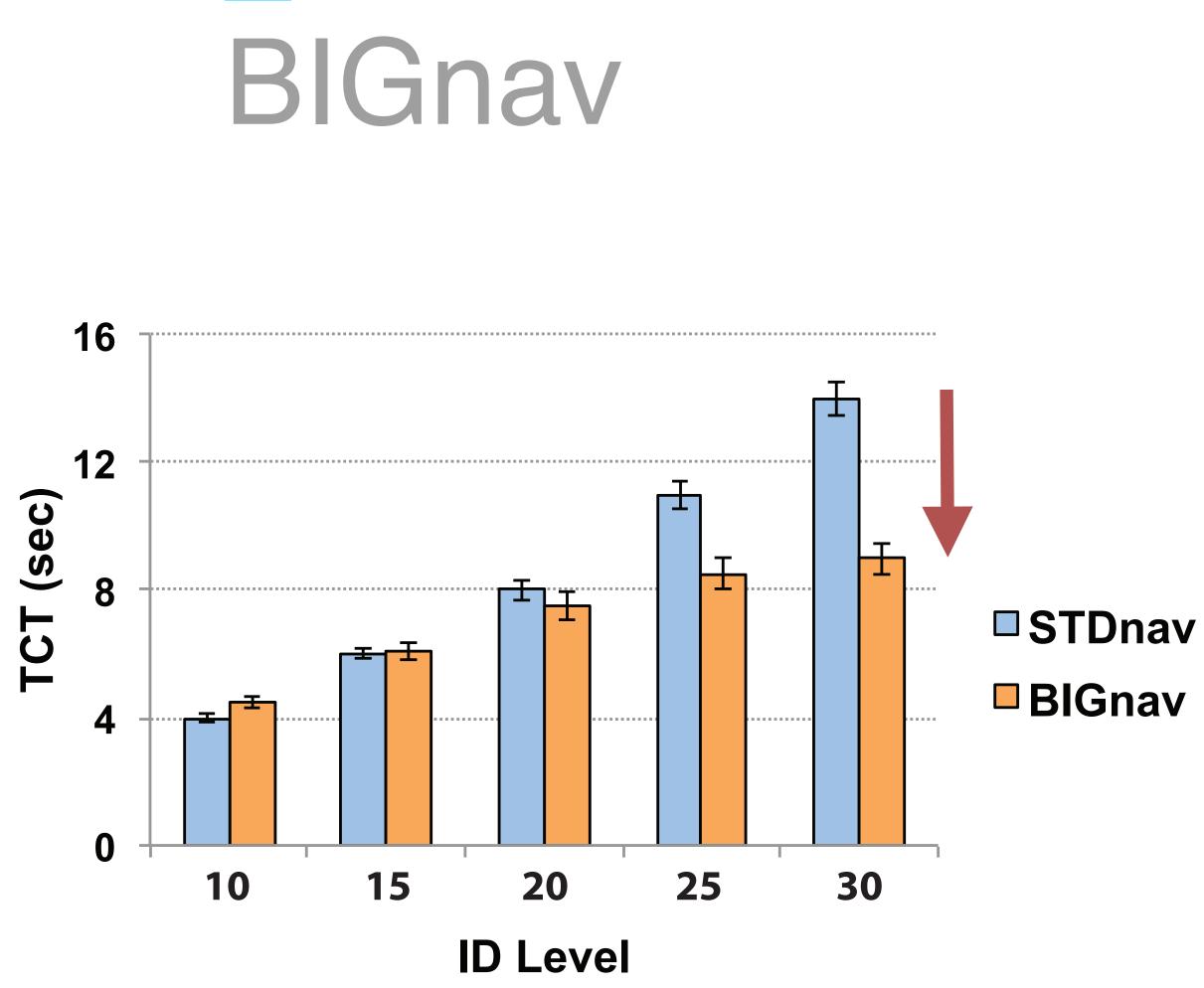
A map application - "3 steps to go to Paris". Europe map featuring large cities with their population as distribution.





A map application - "Navigate to Helsinki". Europe map featuring large cities with their population as distribution.

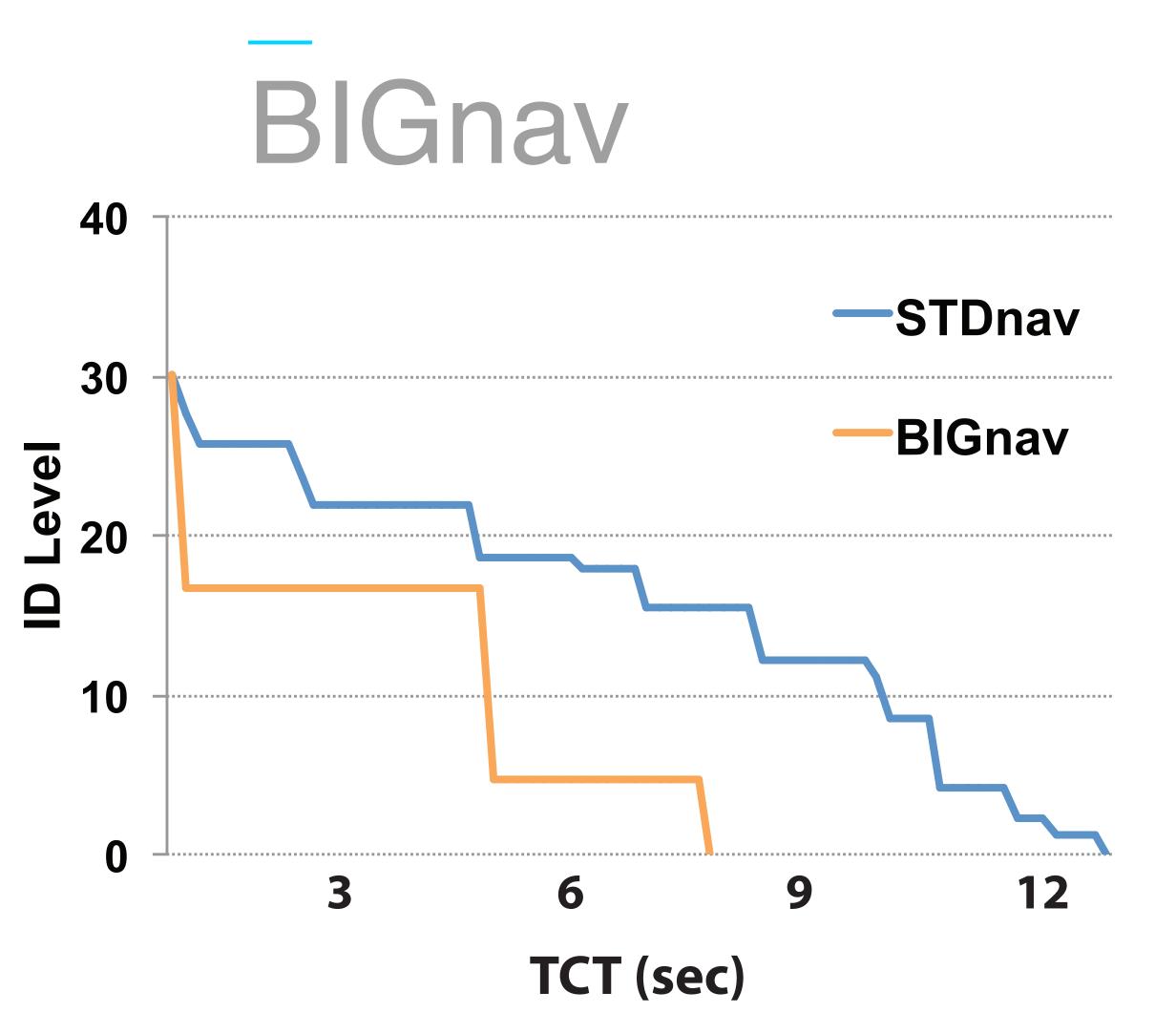




#### Up to 40% faster than pan-and-zoom navigation

Higher gain for targets further away





#### Incurs a high cognitive load

### After each move, long pause before next input

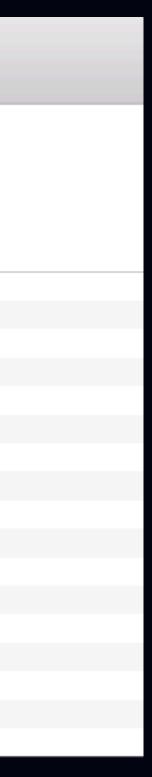
BIG move hard to predict



## Same approach for file retrieval

Liu, Rioul, McGrenere, Mackay, Beaudouin-Lafon, 2018

٠	•	BIGFile	
< Bac		ese -> France -> Creamy -> Brie	
	Geography > 📃 Islands > 📃 Tropical > 📃 Touristic >	🔲 Large > 📄 Hawaii	
	Food > 📃 Dairy > 📃 Cheese		
	History > 🔲 Inventions		
	Education > 📃 Curriculum > 📃 Masters > 📃 German		
	Geography	Apr 5, 2017, 2:02pm	
	Animals	Apr 5, 2017, 2:02pm	
	Computing	Apr 5, 2017, 2:02pm	
	Food	Apr 5, 2017, 2:02pm	
	Transport	Apr 5, 2017, 2:02pm	
	Health	Apr 5, 2017, 2:02pm	
	Entertainment	Apr 5, 2017, 2:02pm	
	History	Apr 5, 2017, 2:02pm	
	Plants	Apr 5, 2017, 2:02pm	
	People	Apr 5, 2017, 2:02pm	
	House & Home	Apr 5, 2017, 2:02pm	
	Education	Apr 5, 2017, 2:02pm	
4	Budget	Apr 5, 2017, 2:02pm	60k
	Essay	Apr 5, 2017, 2:02pm	60k
-	Paper	Apr 5, 2017, 2:02pm	60k
-	Article	Apr 5, 2017, 2:02pm	60k
4	Fireman	Apr 5, 2017, 2:02pm	60k

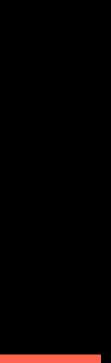




## Same approach for file retrieval

Liu, Rioul, McGrenere, Mackay, Beaudouin-Lafon, 2018

📄 Geography > 📄 Islands	
Food > Dairy > Chee	ese
Geography	
Animals	Static area
Computing	The usual hiera
Food	
Transport	





83

## Same approach for file retrieval

Liu, Rioul, McGrenere, Mackay, Beaudouin-Lafon, 2018

Geography > Islands	Adaptive are Estimated sho
Food > Dairy > Che	ese
Geography	
Animals	
Computing	
Food	
Transport	

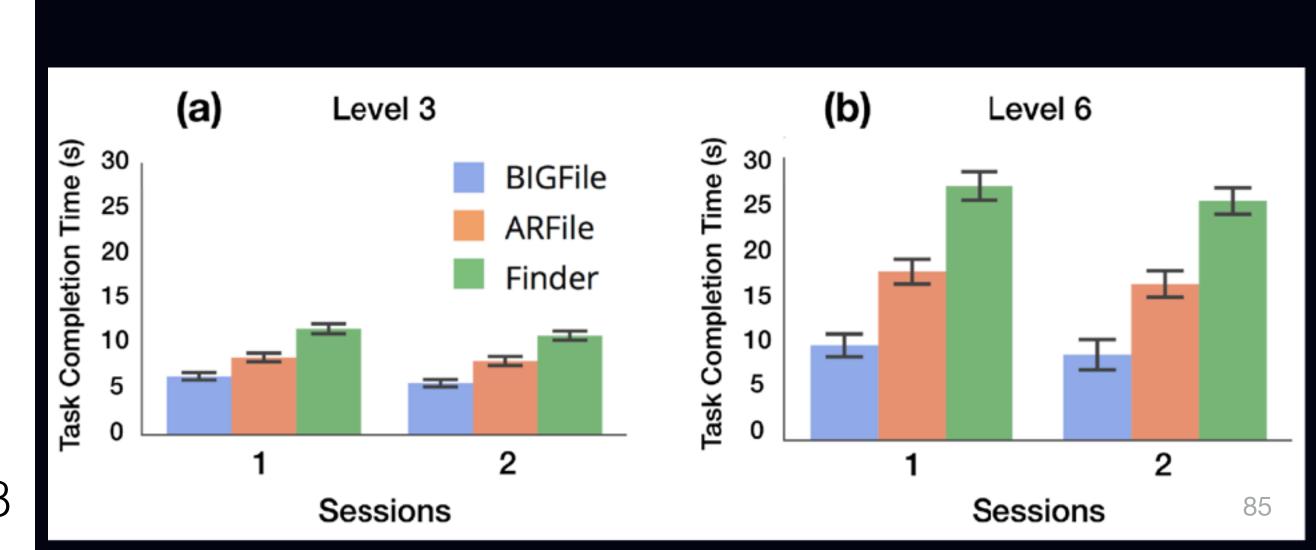


84

## Same approach for file retrieval

Liu, Rioul, McGrenere, Mackay, Beaudouin-Lafon, 2018

### Performance: 44% faster than best technique 64% faster than regular Finder



# Conclusion

#### Information is a fruitful concept for interaction

#### BUT

None of these techniques are available in mainstream interfaces

Other possible applications: text entry, command selection, ...



86

# Conclusion

Theory-driven HCI leads to generative theories that create novel and powerful techniques

Information theory is a source of inspiration and a tool for future human-computer partnerships



# Merci!

# Questions?

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#### http://ex-situ.fr

#### Remerciements

Wendy Mackay Yves Guiard Olivier Rioul Wanyu Liu Nicolas Taffin





lnría

INVENTORS FOR THE DIG

