Chapter 7
Modeling Interaction

Introduction

• A model is a simplification of reality
• Consider…

• Both are simplifications of complex phenomena
• The architect’s model is a description → provides insight into space usage, movement of people, light, shade, etc.
• The physicist’s model is a prediction → gives the ball’s position as a function of time
Descriptive Models

- Descriptive models are everywhere
- Descriptive modeling is at times so simple, the process barely seems like modeling
- Any reduction or partitioning of a problem space qualifies as a descriptive model, for example...

Other names:
- Design space, framework, taxonomy, classification, and often without a name given
- As a partitioned domain, we are empowered to think differently – and critically – about the problem
Descriptive Model Examples

- Politics
- Groupware
- Keyboards
- Two-handed input
- Graphical input [GO]

Big Fuzzy Cloud Model of Politics

- Let’s consider a topic we all know a little about
- Below is a big fuzzy cloud model for politics:

  Politics

- Of course, there is no model – it’s just the thing itself
- How do we go about making a descriptive model of politics?
- Break it down; partition the topic into parts
- What are the things that make up politics?
- How can they be labeled, presented, and organized?
Descriptive Model of Politics

- With Johnston’s model of politics, we are empowered to think differently about politics

Questions:
- Is the model correct?
- Is there a different organization that might work better?
- Is it correct to mirror citizens/communities with state/government?
- Are the five perimeter items sufficient?
- Is federalism an institution (or an idea)?
- Is the model useful?

Most important question

Descriptive Model Examples

- Politics
  - Groupware
    - Keyboards
    - Two-handed input
    - Graphical input

CSCW (Groupware)

- A research topic within HCI is CSCW (computer supported cooperative work)
- Concerned with people working collaboratively using computing technology
- Aka groupware
- Same challenge:
  - How do we go about making a descriptive model of groupware?
  - Break it down; partition the topic into parts
  - What are the things that make up groupware?
  - How can they be labeled, presented, and organized?

Quadrant Model of Groupware

- A descriptive model
- Groupware partitioned into a $2 \times 2$ space
  - Location $\rightarrow$ same place | different places
  - Time $\rightarrow$ same time | different times

<table>
<thead>
<tr>
<th>Same Time</th>
<th>Different Times</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copy boards</td>
<td>Shared Files</td>
</tr>
<tr>
<td>PC Projectors</td>
<td>Shift Work</td>
</tr>
<tr>
<td>Facilitation Services</td>
<td>Kiosks</td>
</tr>
<tr>
<td>Group Decision Room</td>
<td>Team Rooms</td>
</tr>
<tr>
<td>Polling Systems</td>
<td>Group Displays</td>
</tr>
<tr>
<td>Conference Calls</td>
<td>Group Writing</td>
</tr>
<tr>
<td>Graphics and Audio</td>
<td>Computer Conferencing</td>
</tr>
<tr>
<td>Screen Sharing</td>
<td>Conversational Structuring</td>
</tr>
<tr>
<td>Video Teleconferencing</td>
<td>Forms Management</td>
</tr>
<tr>
<td>Spontaneous Meetings</td>
<td>Group Voice Mail</td>
</tr>
</tbody>
</table>

Critiquing the Model

• The quadrant model of groupware was introduced in 1991
• The same questions apply:
  – Is the model correct? Is there a different organization that might work better? Is the model useful? Etc.
• Many of today’s methods of collaborating didn’t exist in 1991
• Contemporary groupware activities include
  – Sharing photos using camera phones, web cams, Skype, social media, blogging, tweeting
• Can these be positioned in the quadrant model of groupware? (probably; give it a try)

Descriptive Model Examples

• Politics
• Groupware
  • Keyboards
  • Two-handed input
  • Graphical input
Keyboards

- Keyboards date at least to the 1870s with the introduction of the Scholes-Glidden typewriter keyboard
- Today’s keyboards retain the same core letter arrangement (qwerty), but have many extra keys
- 100+ keys can produce a wide variety of letters, symbols, commands, etc.
- Same challenge:
  - How do we go about making a descriptive model of keyboards?
  - Break it down; partition the topic into parts
  - What are the things that make up keyboards?
  - How can they be labeled, presented, and organized?

Key-Action Model (KAM)\textsuperscript{1}

- A descriptive model
- Three categories of keys:
  - Symbol keys \(\rightarrow\) produce graphic symbols (e.g., A)
  - Executive keys \(\rightarrow\) invoke actions (e.g., ESC)
  - Modifier keys \(\rightarrow\) modify effect of other keys (e.g., CTRL)

Critiquing the Model

• Nice visualization
  – Reveals organization of the keyboard in terms of symbol, executive, and modifier keys

• Questions:
  – Is the model correct? Do all keys fit the model? Are there additional categories to improve the model? Do some keys fit more than one category? Can the model be applied to other keyboards, such as mobile phone keyboards or soft keyboards? Is the model useful? Etc.

• Note: Red dots on previous slide identify executive keys that are not mirrored (excluding function keys)

• Hmm… There seems to be a 3:18 right-side bias!

Descriptive Model Examples

• Politics
• Groupware
• Keyboards
  • Two-handed input
  • Graphical input
Two-handed Input

- Humans not only have two hands, they use their hands differently
- Most people have a hand preference (*Which hand do you use to write?*)
- Study of hand usage is called *laterality* or *bimanual control*
- Guiard undertook such a study, examining the roles of the preferred and non-preferred hands in common tasks
- The result is a descriptive model

Guiard’s Model of Bimanual Control

<table>
<thead>
<tr>
<th>Hand</th>
<th>Role and Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-preferred</td>
<td>- Leads the preferred hand</td>
</tr>
<tr>
<td></td>
<td>- Sets the spatial frame of reference for the preferred hand</td>
</tr>
<tr>
<td></td>
<td>- Performs coarse movements</td>
</tr>
<tr>
<td>Preferred</td>
<td>- Follows the non-preferred hand</td>
</tr>
<tr>
<td></td>
<td>- Works within established frame of reference set by the non-preferred hand</td>
</tr>
<tr>
<td></td>
<td>- Performs fine movements</td>
</tr>
</tbody>
</table>

Consider the bulleted points above in terms of the sketch on the right.

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Critiquing the Model

- Guiard’s model was not developed using examples from computing
- Paul Kabbash, a graduate student at the University of Toronto in the 1990s, came across Guiard’s model as part of his research in two-handed computer input
- Guiard’s model provided insight to more fully understand the roles of the preferred and non-preferred hands for computer input
- Widely used since for analysing and understanding two-handed computer input, for example…

Scrolling

- The table below deconstructs scrolling as it relates to other common computing tasks that coexist with scrolling

<table>
<thead>
<tr>
<th>Task</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scrolling</td>
<td>Precedes/overlaps other tasks</td>
</tr>
<tr>
<td></td>
<td>Sets the frame of reference</td>
</tr>
<tr>
<td></td>
<td>Minimal precision needed (coarse)</td>
</tr>
<tr>
<td>Selecting, editing, reading, drawing, etc.</td>
<td>Follows/overlaps scrolling</td>
</tr>
<tr>
<td></td>
<td>Works within frame of reference set by scrolling</td>
</tr>
<tr>
<td></td>
<td>Demands precision (fine)</td>
</tr>
</tbody>
</table>

- Do you see the similarity with Guiard’s model of bimanual control?
- What does this suggest? (next slide)
Non-preferred Hand Scrolling

- Guiard’s model of bimanual control suggests that scrolling is a task well suited to the non-preferred hand:

- But, what about the wheel mouse, introduced in 1996 by Microsoft as the *Intellimouse*?
- How to get scrolling into the non-preferred hand?

Re-engineered *Intellimouse*

- A presentation rationalizing non-preferred hand scrolling (in view of Guiard’s model of bimanual control) was given at Microsoft in Feb 1998 using a re-engineered *Intellimouse*:

- In fact, the presentation was given twice the same day (a.m. → “mouse group” | p.m. → “keyboard group”)
- The case for scrolling via the non-preferred hand was persuasive *Two-years later*
Microsoft Office Keyboard

- Includes left-side wheel (roller) for scrolling via the non-preferred hand (for right-handed users):

- The left-side scroll wheel was eventually discontinued in later releases of Microsoft keyboards
- Momentum and popularity of the wheel mouse were too much to overcome

Post Script

- Guiard’s model for bimanual control remains widely used in human-computer interaction
- Google Scholar returns 265 citations “since 2010” to Guiard’s 1987 paper (“Asymmetric division of labor in…”)
- Most citations are from research papers in HCI
Descriptive Model Examples

- Politics
- Groupware
- Keyboards
- Two-handed input
- Graphical input

Graphical Input

- Considerable research on GUIs followed the successful introduction of the Apple Macintosh in 1984
  - Common interactive techniques (tasks):
    - pointing, dragging, selecting, inking, rubber-banding, texting
  - Common technologies (devices):
    - mouse, trackball, touch panel, joystick, stylus, finger
- How can the tasks and devices be reconciled and understood to promote better designs?
- Buxton commented on…
  - “…the lack of a vocabulary that is capable of capturing salient features of interactive techniques and technologies in such a way as to afford finding better matches between the two”¹
- To address this, Buxton presented a three-state model of graphical input (next slide)

Buxton’s Three State Model of Graphical Input

- A descriptive model
- Expresses GUI interaction in terms of three states
- Mouse example: (different for other devices)
  - State 0 \(\rightarrow\) out of range
  - State 1 \(\rightarrow\) tracking
  - State 2 \(\rightarrow\) dragging

Application of Buxton’s Model

- In 1994 Apple introduced the Trackpad on its Powerbook 500 notebook computer
- Soon after, the Trackpad (usually called a touchpad) became the standard pointing device on notebook computers
- Besides physical buttons to mimic mouse buttons, a touchpad includes “lift and tap” to implement button down/up actions using touch
- But, lift-and-tap actions are error prone \(\rightarrow\) during a tap, if the finger moves before lifting, a dragging action is sometimes invoked, instead of a click
Analysis

- Let’s analyse and compare common touchpad and mouse interactions, guided by Buxton’s three-state model (next slide)
Hmm… Moment

- But… touchpads are capable of sensing finger pressure (like the pressure of a finger on a mouse button)
- Descriptive models → hmm… moments
- Touchpad protocols
  - Mouse emulation mode
  - Native mode
The Tactile Touchpad

- Uses native x-y-z mode (z = finger pressure)
- Implements button down (state 2) by “pressing harder”
- Button click feedback provided by relay below touchpad
- Design guided by Buxton’s three-state model

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**Demo**

http://www.youtube.com/watch?v=fxfu-Yo6yEk
Three-state Touch Products


See the links below for press describing these products’ use of three-state interaction, with reference to the tactile touchpad

http://www.touchusability.com/blog/2008/10/14/three-state-touch-now-apple-has-it-too.html

Post Script

- Buxton’s three-state model remains widely used in human-computer interaction
- Google Scholar returns 89 citations since 2010 to Buxton’s 1990 paper (“A three state model of…”)
- Contemporary applications include
  - Models for preview and undo
  - Puck and stylus input for two-handed interaction
  - Docking tasks for tabletop displays
  - Camera control for navigating animated scenes
  - Modeling multi-touch on touchscreens
  - Modeling panning and zooming on touchscreens
  - Modeling selection of moving targets
  - Modeling the rotation mode of a 3 DOF mouse
Predictive Models

• A predictive model is an equation
• Predicts the outcome on a criterion variable (aka dependent variable or human response) based on the value of one or more predictor variables (aka independent variables)
• Note: the predictor variables must be ratio-scale attributes (See HCI:ERP for discussion)
• Predictive models, like descriptive models, allow a problem space to be explored
• However, predictive models deal with numbers, not concepts
Why Use Predictive Models

- Card et al. presented perhaps the first predictive model in HCI.¹ In many respects, their work was straightforward experimental research; but they went further:
  - “While these empirical results are of direct use in selecting a pointing device, it would obviously be of greater benefit if a theoretical account of the results could be made. For one thing, the need for some experiments might be obviated; for another, ways of improving pointing performance might be suggested.”
- This is a call for the use of predictive models in HCI
- They went on to present predictive models using Fitts’ law (which we meet shortly)


Predictive Model Examples

- Linear prediction equation
- Fitts’ law
- Choice reaction time
- Keystroke-level model (KLM)
- Skill acquisition
- More than one predictor
Linear Prediction Equation

- The basic prediction equation expresses a linear relationship between a predictor variable (x) and a criterion variable (y):

$$y = mx + b$$

Linear Regression

- A linear prediction equation is built using a statistical procedure known as linear regression
- Goal:
  - Given a set of x-y sample points, find the coefficients $m$ and $b$ (previous slide) for the line that minimizes the squared distances (least squares) of the points from the line
- The result is a prediction equation that gives the best estimate of $y$ in terms of $x$
- The assumption, of course, is that the relationship is linear
- Want the details? Just enter “linear regression” or “least squares” into Google or Wikipedia
Example

- A research project investigated text entry on soft keyboards
- The research also asked...
  - Can stylus tapping entry speed be predicted from touch typing entry speed?
- Touch typing speed is the predictor variable ($x$ measured in a pre-test)
- Stylus typing speed is the criterion variable ($y$ measured experimentally)
- Data and scatter plot


Data and Scatter Plot

There seems to be a relationship: Faster touch typists seem to be faster at stylus tapping.

Questions:
What is the prediction equation?
How strong is the relationship?
Prediction Equation

Note: The prediction equation explains 27% of the variation in the data – a modest predictor, at best.

Predictive Model Examples

• Linear prediction equation
• Fitts’ law
• Choice reaction time
• Keystroke-level model (KLM)
• Skill acquisition
• More than one predictor
Digress to Separate Presentation on

Fitts’ Law

(return when done)

Predictive Model Examples

- Linear prediction equation
- Fitts’ law
- Choice reaction time
- Keystroke-level model (KLM)
- Skill acquisition
- More than one predictor
Choice Reaction Time

• Given \( n \) stimuli, associated one-for-one with \( n \) responses, the time to react to the onset of a stimulus is the *choice reaction time*.  

• Modeled by the Hick-Hyman law: 

\[
RT = a + b \log_2(n + 1)
\]

• Coefficients:  
  \( a \approx 200 \text{ ms} \)  
  \( b \approx 150 \text{ ms/bit} \)

• An Information processing model (like Fitts' law)


HCI Applications

• Not many, but…
  – A telephone operator selects among ten buttons when a light behind a button turns on\(^1\)
  – Time to select items in a hierarchical menu (visual search eliminated by practicing participants to expert levels)\(^2\)
  – Activation time for mode switching with non-dominant hand in a tablet interface\(^3\)

• Difficult to apply because additional behaviours are often present, such as visual search or movement

Hick-Hyman Law and Information

• Like Fitts' law, the information content \((H)\) of a choice reaction time task is given by the log term

• Examples (without the “+1”)
  – With 8 stimuli, \(H = \log_2(8) = 3\) bits
  – With 26 stimuli, \(H = \log_2(26) \approx 4.70\) bits

• An interesting variation of the Hick-Hyman law occurs if the stimuli occur with different frequencies

• If the frequency of activation differs by stimulus, the information content of the task goes down because there is a small opportunity for the user to anticipate the stimulus

• Before looking at the example in \(\text{HCI:ERP}\) (next slide), [click here] to examine an Excel spreadsheet demonstrating the information for random and non-random cases

\[
\begin{array}{|c|c|c|c|}
\hline
\text{Letter} & \text{Frequency} & \text{Probability (p)} & p \log_2(\frac{1}{p} + 1) \\
\hline
a & 24373121 & 0.0810 & 0.3028 \\
b & 4762838 & 0.0158 & 0.0950 \\
c & 8982417 & 0.0299 & 0.1525 \\
d & 10805580 & 0.0359 & 0.1742 \\
e & 37907119 & 0.1260 & 0.3981 \\
f & 7486889 & 0.0249 & 0.1335 \\
g & 5143059 & 0.0171 & 0.1008 \\
h & 18058207 & 0.0600 & 0.2486 \\
i & 21820970 & 0.0729 & 0.2819 \\
j & 474021 & 0.0016 & 0.0147 \\
k & 1720909 & 0.0067 & 0.0427 \\
l & 11730498 & 0.0390 & 0.1846 \\
m & 7391366 & 0.0246 & 0.1322 \\
n & 21402466 & 0.0711 & 0.2783 \\
o & 23216552 & 0.0772 & 0.2935 \\
p & 5719422 & 0.0190 & 0.1092 \\
q & 297237 & 0.0010 & 0.0099 \\
r & 17897352 & 0.0695 & 0.2471 \\
s & 19059775 & 0.0633 & 0.2578 \\
t & 28691274 & 0.0954 & 0.3358 \\
u & 8022379 & 0.0267 & 0.1404 \\
v & 2835696 & 0.0094 & 0.0636 \\
w & 6505294 & 0.0216 & 0.1203 \\
x & 562732 & 0.0019 & 0.0170 \\
y & 5910495 & 0.0196 & 0.1119 \\
z & 93172 & 0.0003 & 0.0036 \\
\hline
\end{array}
\]

Note: \(\log_2(26) \approx 4.70\)
Predictive Model Examples

- Linear prediction equation
- Fitts’ law
- Choice reaction time
- Keystroke-level model (KLM)
- Skill acquisition
- More than one predictor

Keystroke-Level Model (KLM)¹ ²

- One of the earliest and most comprehensive models in HCI
- Developed specifically for predicting human performance with interactive computing systems
- Predicts expert error-free task completion times
- Elements of a KLM prediction
  - Task (or a series of tasks)
  - Method used
  - Command language of the system
  - Motor skill parameters of the user
  - Response time parameters of the system

Why Use the KLM?

• Consider a task such as “delete a file”
• Perhaps there are two ways to do the task:
  1. Mouse + menu selection
  2. Keyboard + command entry
• The KLM can predict the time for each method
• If used at the design stage, design alternatives may be considered and compared \(\rightarrow\) design choices follow

A KLM Prediction

• A task is broken into a series of subtasks
• Total predicted time is the sum of the subtask times:

\[
t_{\text{EXECUTE}} = t_K + t_P + t_H + t_D + t_M + t_R
\]

• Operators:
  – K \(\rightarrow\) keystroking  P \(\rightarrow\) pointing  H \(\rightarrow\) homing
  – D \(\rightarrow\) drawing  M \(\rightarrow\) mental prep  R \(\rightarrow\) system response
• Some operators are omitted or repeated, depending on the task (e.g., if \(n\) keystroking operations are required, \(t_K\) becomes \(n \times t_K\))
• Operator values (next slide)
KLM Operators and Values

<table>
<thead>
<tr>
<th>Operator</th>
<th>Description</th>
<th>Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>Press a key or button</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pressing a modifier key (e.g., shift) counts as a separate operation. Time varies with typing skill:</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Best typist (135 wpm)</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td>Good typist (90 wpm)</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>Average skilled typist (55 wpm)</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>Average non-secretary typist (40 wpm)</td>
<td>0.28</td>
</tr>
<tr>
<td></td>
<td>Typing random letters</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td>Typing complex code</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td>Worst typist (unfamiliar with keyboard)</td>
<td>1.20</td>
</tr>
<tr>
<td>P</td>
<td>Point with a mouse</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Empirical value based on Fitts' law. Range from 0.8 to 1.5 seconds. Operator does not include the button click at the end of a pointing operation</td>
<td>1.10</td>
</tr>
<tr>
<td>H</td>
<td>Home hand(s) on keyboard or other device</td>
<td>0.40</td>
</tr>
<tr>
<td>D(n,o,l)</td>
<td>Draw n straight-line segments of total length l. Drawing with the mouse constrained to a grid</td>
<td>0.9 n + 0.16 l</td>
</tr>
<tr>
<td>M</td>
<td>Mentally prepare</td>
<td>1.35</td>
</tr>
<tr>
<td>R(t)</td>
<td>Response by system</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Different commands require different response times. Counted only if the user must wait</td>
<td></td>
</tr>
</tbody>
</table>

Original KLM Experiment

- The KLM was validated in an experiment with fourteen tasks performed using various methods and systems.
- Example: Task 1 \(\rightarrow\) Replace a 5-letter word with another word (one line from previous task).
- Using one system, POET, the task was broken down as follows:

<table>
<thead>
<tr>
<th>Command</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jump to next line</td>
</tr>
<tr>
<td>Issue Substitute command</td>
</tr>
<tr>
<td>Type new word</td>
</tr>
<tr>
<td>Terminate new word</td>
</tr>
<tr>
<td>Type old word</td>
</tr>
<tr>
<td>Terminate old word</td>
</tr>
<tr>
<td>Terminate command</td>
</tr>
</tbody>
</table>

- 4 mental operations + 15 keystroking operations, hence \(\rightarrow\)
KLM Prediction (Example)

\[ t_{\text{EXECUTE}} = 4 \times t_M + 15 \times t_K \]

- M set to 1.35 seconds (two slides back)
- K set to 0.23 seconds, based on a 5-minute pre-test
- So...

\[ t_{\text{EXECUTE}} = 4 \times 1.35 + 15 \times 0.23 \]
\[ = 8.85 \text{ seconds} \]

- This is the prediction
- What about the observation? (next slide)
Sensitivity Analysis

- If parameters are treated as variables, the sensitivity of predictions to changes in parameters can be assessed

Implication: The preferred method changes with the distance to the misspelled word.

Modern Applications

- Mouse interaction was just emerging when the KLM was introduced
- An obvious KLM update is to replace the pointing constant ($t_p$) with a Fitts’ law prediction equation, as appropriate for the device (e.g., mouse vs. touchpad) and task (e.g., point-select vs. drag-select)
- For example, using the Fitts’ law equation given earlier for the mouse:

$$t_p = 0.159 + 0.204 \times \log_2\left(\frac{A}{W} + 1\right)$$
Pointing Operator – Update

- For example, a mouse point-select operation over 3.2 cm to click a 1.2 cm wide toolbar button should take about...

$$t_p = 0.159 + 0.204 \times \log_2 \left( \frac{3.2}{1.2} + 1 \right) = 0.45 \text{ seconds}$$

- If the same task involves moving the pointer 44.6 cm, the prediction becomes...

$$t_p = 0.159 + 0.204 \times \log_2 \left( \frac{44.6}{1.2} + 1 \right) = 1.22 \text{ seconds}$$

Pointing Operator – Example

- Develop KLM mouse and keyboard predictions for the GUI screen below
- Task: Change the font and style for “M K” to bold, Arial
Mouse Analysis

- Operations:

<table>
<thead>
<tr>
<th>Mouse Subtasks</th>
<th>KLM Operators</th>
<th>$t_E$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drag across text to select &quot;M K&quot;</td>
<td>M P[2.5, 0.5]</td>
<td>0.686</td>
</tr>
<tr>
<td>Move pointer to Bold button and click</td>
<td>M P[13, 1]</td>
<td>0.936</td>
</tr>
<tr>
<td>Move pointer to Font drop-down button and click</td>
<td>M P[3.3, 1]</td>
<td>0.588</td>
</tr>
<tr>
<td>Move pointer down list to Arial and click</td>
<td>M P[2.2, 1]</td>
<td>0.501</td>
</tr>
</tbody>
</table>

$\sum t_p = 2.71$

- Prediction:

$$t_{EXECUTE} = 4 \times t_M + \sum t_p = 4 \times 1.35 + 2.71 = 8.11 \text{ seconds}$$

Keyboard Analysis

- Operations:

<table>
<thead>
<tr>
<th>Keyboard Subtasks</th>
<th>KLM Operators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Select text</td>
<td>M K[shift] 3K[→]</td>
</tr>
<tr>
<td>Convert to boldface</td>
<td>M K[ctrl] K[b]</td>
</tr>
<tr>
<td>Activate Format menu and enter Font sub-menu</td>
<td>M K[alt] K[c] K[f]</td>
</tr>
<tr>
<td>Type a (&quot;Arial&quot; appears at top of list)</td>
<td>M K[a]</td>
</tr>
<tr>
<td>Select &quot;Arial&quot;</td>
<td>K[↓] K[enter]</td>
</tr>
</tbody>
</table>

- Prediction:

$$t_{EXECUTE} = 4 \times t_M + 12 \times t_K = 4 \times 1.35 + 12 \times 0.75 = 14.40 \text{ seconds}$$

Use “typing complex codes” ($t_k = 0.75 \text{ s}$)
Sensitivity Analysis

• The keyboard prediction is sensitive to the parameter $t_K$, the keystroking time

• If $t_K$ is allowed to vary, what is the effect on the predictions? (see below)

![Graph showing sensitivity analysis]

**Implication:** The mouse is faster than the keyboard, except for $t_K \leq 0.2$ seconds (which is unlikely, given the nature of the keyboard actions).

Contemporary Uses of the KLM

• The KLM continues to be widely used in HCI

• Some contemporary uses include…
  – Attention shifts with mobile phones
  – Stylus-based circling gestures
  – Managing folders and messages in e-mail applications
  – Predictive text entry on mobile phones
  – Task switching in multi-monitor systems
  – Mode switching on tablet PCs
  – Distractions in in-vehicle information systems (IVIS)

See HCI:ERP for citations
Validating Custom KLMs

- When researchers build a custom KLM (previous slide), an experiment is usually conducted to validate the model.
- What is the implication if observations ≠ predictions?
- Hinckley et al. note…

  [The discrepancy] shows where the techniques deviate from the model, indicating the presence of hidden costs. These costs might include increased reaction time resulting from planning what to do next, mental pauses, or delays while the user attends to visual feedback after performing an action. Our methodology cannot attribute these costs to a specific cause. It just lets us deduce that a hidden cost must exist in a specific portion of the task. This is sufficient to generate many insights as to where the bottlenecks to performance lie and what parts of a technique might be improved.

KLM and Mobile Phone Keypad

- Since input uses a single finger or thumb, the keystroking operator can be replaced with a pointing operator

\[ t_{P(index\;finger)} = 0.165 + 0.052 \log_2 \left( \frac{A}{W} + 1 \right) \]

\[ t_{P(thumb)} = 0.176 + 0.064 \log_2 \left( \frac{A}{W} + 1 \right) \]


KLM and Predictive Text Entry

- Interesting because of the combination of keystroking/pointing operations and mental operations
- Consider entering “beep” on a mobile phone keypad using predictive text entry (T9):

![Mobile phone keypad](for reference)

- Perhaps the following…

![Keys Display](KLM model?)

KLM Operators for “beep”

- Perhaps the following…

![Mental operator for “physical matching”](in this case, between the word on the display and the word in the user’s mind)

- Two questions:
  1. Where should mental operators be placed?
  2. What value should the mental operator assume?
Expert Behaviour

• Experts know the T9 key sequences for common words (i.e., no need for \( M_P \) at end of word):
  - \( \text{the} \rightarrow 8430 \)
  - \( \text{of} \rightarrow 630 \)
  - \( \text{and} \rightarrow 2630 \)

• But, how far down a word frequency list\(^1\) does such behaviour extend?

• What about ambiguous words?
  - \( \text{if} \rightarrow 43n0 \)
  - \( \text{no} \rightarrow 66n0 \)
  - \( \text{beep} \rightarrow 2337nmmn0 \)

\(\text{“beep” is at rank 20,767. Even experts will likely require the } M_P \text{ operator at the end of the word (unless, for some reason, “beep” is a word they commonly enter).}\)

\(^1\) The word-frequency list used here is the 64,000 word list described by Silfverberg et al. (2000).

Ambiguous Words

• Below is a list of the top ten words requiring a press of next

<table>
<thead>
<tr>
<th>Rank</th>
<th>Word</th>
<th>Keystrokes</th>
<th>Higher Ranking Colliding Word (rank)</th>
</tr>
</thead>
<tbody>
<tr>
<td>47</td>
<td>if</td>
<td>43n0</td>
<td>he (15)</td>
</tr>
<tr>
<td>51</td>
<td>no</td>
<td>66n0</td>
<td>on (13)</td>
</tr>
<tr>
<td>63</td>
<td>then</td>
<td>8436n0</td>
<td>them (57)</td>
</tr>
<tr>
<td>72</td>
<td>me</td>
<td>63n0</td>
<td>of (2)</td>
</tr>
<tr>
<td>78</td>
<td>these</td>
<td>84373n0</td>
<td>there (35)</td>
</tr>
<tr>
<td>105</td>
<td>go</td>
<td>46n0</td>
<td>in (6)</td>
</tr>
<tr>
<td>118</td>
<td>us</td>
<td>87n0</td>
<td>up (56)</td>
</tr>
<tr>
<td>159</td>
<td>home</td>
<td>4663n0</td>
<td>good (115)</td>
</tr>
<tr>
<td>227</td>
<td>night</td>
<td>64448n0</td>
<td>might (141)</td>
</tr>
<tr>
<td>298</td>
<td>war</td>
<td>927n0</td>
<td>was (10)</td>
</tr>
</tbody>
</table>

\(M_P\) operators?
Heuristics for $M_p$ Operator

- It is not possible to precisely know when a user will hesitate to perform an $M_p$ operation – a physical match between the word on the display and the word in the user’s mind
- Two approaches for KLM modeling with $M_p$:
  - All-in → include $M_p$ at every reasonable juncture
  - All-out → exclude all $M_p$ operations
- The two approaches will produce upper bound (all-in) and lower bound (all-out) predictions

KLM and Visual Search

- Interfaces on smart phone supporting word prediction or word completion typically provide the user with a list of choices (“candidates”) as entry proceeds
- Instead of performing a “physical match”, the user performs a “visual search”
- A model for visual search time, given $n$ items to search, was given earlier (Chapter 2)
- How can visual search be included as a KLM mental operator?
- Let’s explore with a demo (next slide)
Use PhoneKeypad Experiment software from HCI:ERP web site:
http://www.yorku.ca/mack/HCIbook/

Mental Operator for Visual Search (M_V)

- Two scenarios using “vegetables” as an example:

  8 3 4 M_V W

  8 M_V 3 M_V 4 M_V W

- Some considerations:
  - A long candidate list bears a cost since it takes longer to visually scan but brings benefit since the desired word appears sooner.
  - Viewing the candidate list after each keystroke adds time to the interaction (cost) but allows entry of the intended word at the earliest opportunity (benefit).
  - There are different methods of selecting a candidate (e.g., direct selection, keystroke navigation).
Updating the KLM’s Mental Operator

- Drawing on operators from Card et al. and from the reaction time experiments in Chapter 2 herein…

<table>
<thead>
<tr>
<th>Proposed Mnemonic</th>
<th>Task</th>
<th>Execution Time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ms</td>
<td>Simple Reaction</td>
<td>240 [105 – 470]</td>
</tr>
<tr>
<td>Mf</td>
<td>Physical Matching</td>
<td>310 [130 – 640]</td>
</tr>
<tr>
<td>Mn</td>
<td>Name Matching</td>
<td>380 [155 – 810]</td>
</tr>
<tr>
<td>Mc</td>
<td>Class Matching</td>
<td>450 [180 – 980]</td>
</tr>
<tr>
<td>M6</td>
<td>Choice Reaction</td>
<td>200 + 150 log2(N + 1)</td>
</tr>
<tr>
<td>M7</td>
<td>Visual Search</td>
<td>498 + 41 N</td>
</tr>
</tbody>
</table>

Predictive Model Examples

- Linear prediction equation
- Fitts’ law
- Choice reaction time
- Keystroke-level model (KLM)
- Skill acquisition
- More than one predictor
Skill Acquisition

- When learning a skill, we begin as novices
- Initial performance is poor, but, with practice, we acquire skill
- With continued practice, we become proficient, perhaps experts
- The novice to expert transition is well suited to predictive modeling
- Dependent variable \( \rightarrow \) proficiency (typically, the time or speed in doing a task)
- Independent variable \( \rightarrow \) amount of practice (e.g., hours, days, months, blocks, sessions)

Power Law of Learning

- Relationship between proficiency and practice is non-linear:
  - At first, a small amount of practice yields substantial improvement
  - Later, the same “small amount of practice” yields only a slight improvement
- Relationship best expressed by a power function:
  \[
  y = b \times x^a \quad \text{(general form)} \\
  T_n = T_1 \times n^a \quad \text{(power law of learning)}
  \]
  where...
  \( T_n \rightarrow \) time to do the task on the \( n \)th trial
  \( T_1 \rightarrow \) time to do the task on the 1st trial (a constant)
  \( n \rightarrow \) trial indicator (e.g., hours, days, blocks, sessions)
  \( a \rightarrow \) a constant setting the shape of the curve

Note: \( a \) is negative since task completion time decreases with practice
Speed Variation

• Dependent variable can be speed ($S$), the reciprocal of time
• Model predicts “tasks per unit time” (e.g., words per minute)
• Mathematical form:

$$S_n = S_1 \times n^a$$

where…
$S_n \rightarrow$ speed on the $n$th trial
$S_1 \rightarrow$ speed on the 1st trial (a constant)
$n \rightarrow$ trial indicator (e.g., hours, days, blocks, sessions)
$a \rightarrow$ a constant setting the shape of the curve

Note: $a$ is positive and $<1$ reflecting the diminishing return with practice

Curve Shapes

Predicting time

$$T_n = T_1 \times n^a$$

Predicting speed

$$S_n = S_1 \times n^a$$

[click here] to open Excel spreadsheet
(PowerLawOfLearning.xlsx)
Example

• An experiment compared two soft keyboards for text entry\(^1\)
  – Qwerty → conventional letter arrangement
  – Opti → optimized to minimize finger or stylus movement

• Qwerty expected to be faster initially
• Opti expected to be faster with practice
• Participants performed 20 sessions of text entry; results →


Results

<table>
<thead>
<tr>
<th>Session</th>
<th>Qwerty (wpm)</th>
<th>Opti (wpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>28.44</td>
<td>16.68</td>
</tr>
<tr>
<td>2</td>
<td>29.98</td>
<td>21.06</td>
</tr>
<tr>
<td>3</td>
<td>31.56</td>
<td>24.80</td>
</tr>
<tr>
<td>4</td>
<td>32.62</td>
<td>27.26</td>
</tr>
<tr>
<td>5</td>
<td>33.20</td>
<td>29.18</td>
</tr>
<tr>
<td>6</td>
<td>34.52</td>
<td>31.04</td>
</tr>
<tr>
<td>7</td>
<td>34.14</td>
<td>33.08</td>
</tr>
<tr>
<td>8</td>
<td>34.68</td>
<td>34.16</td>
</tr>
<tr>
<td>9</td>
<td>35.66</td>
<td>34.72</td>
</tr>
<tr>
<td>10</td>
<td>36.77</td>
<td>35.69</td>
</tr>
<tr>
<td>11</td>
<td>38.95</td>
<td>37.22</td>
</tr>
<tr>
<td>12</td>
<td>37.36</td>
<td>38.75</td>
</tr>
<tr>
<td>13</td>
<td>38.50</td>
<td>39.95</td>
</tr>
<tr>
<td>14</td>
<td>38.65</td>
<td>40.73</td>
</tr>
<tr>
<td>15</td>
<td>39.12</td>
<td>40.68</td>
</tr>
<tr>
<td>16</td>
<td>39.00</td>
<td>41.85</td>
</tr>
<tr>
<td>17</td>
<td>38.20</td>
<td>42.74</td>
</tr>
<tr>
<td>18</td>
<td>39.85</td>
<td>43.55</td>
</tr>
<tr>
<td>19</td>
<td>40.16</td>
<td>43.91</td>
</tr>
<tr>
<td>20</td>
<td>40.30</td>
<td>44.29</td>
</tr>
</tbody>
</table>

Crossover at session 11

Power law of learning?
(next slide)
Power Law of Learning

![Graph showing the Power Law of Learning]

Log-log Model

- If the $x$ and $y$ data are transformed to log scales, the relationship is linear
- Example:¹

![Graph showing the Log-log Model]

$T_p = 2.20 \times n^{-0.13}$

Predictive Model Examples

• Linear prediction equation
• Fitts’ law
• Choice reaction time
• Keystroke-level model (KLM)
• Skill acquisition
  • More than one predictor

More Than One Predictor

• A prediction equation can have more than one predictor:

\[ y = a + b_1 x_1 + b_2 x_2 + b_3 x_3 + \ldots \]

• In statistics, the technique is called *multiple regression*
Hypothetical Example

- Research question:
  - Is there a relationship between the time to learn a computer game and the age and computing habits of players?
- Dependent variable:
  - $y \rightarrow$ the time to reach a criterion score
- Predictor variables:
  - $x_1 \rightarrow$ age of player
  - $x_2 \rightarrow$ daily computer use in hours
- The experiment involved 14 participants (next slide)

Data

<table>
<thead>
<tr>
<th>Participant</th>
<th>Time To Reach Criterion (hours)</th>
<th>Age (years)</th>
<th>Daily Computer Usage (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>2.3</td>
<td>16</td>
<td>8</td>
</tr>
<tr>
<td>P2</td>
<td>2.1</td>
<td>17</td>
<td>7</td>
</tr>
<tr>
<td>P3</td>
<td>2.5</td>
<td>18</td>
<td>8</td>
</tr>
<tr>
<td>P4</td>
<td>3.6</td>
<td>23</td>
<td>6</td>
</tr>
<tr>
<td>P5</td>
<td>2.6</td>
<td>25</td>
<td>7</td>
</tr>
<tr>
<td>P6</td>
<td>5.3</td>
<td>26</td>
<td>5</td>
</tr>
<tr>
<td>P7</td>
<td>4.8</td>
<td>29</td>
<td>6</td>
</tr>
<tr>
<td>P8</td>
<td>6.1</td>
<td>31</td>
<td>4</td>
</tr>
<tr>
<td>P9</td>
<td>7.2</td>
<td>32</td>
<td>5</td>
</tr>
<tr>
<td>P10</td>
<td>7.3</td>
<td>35</td>
<td>3</td>
</tr>
<tr>
<td>P11</td>
<td>6.4</td>
<td>37</td>
<td>4</td>
</tr>
<tr>
<td>P12</td>
<td>6.1</td>
<td>38</td>
<td>2</td>
</tr>
<tr>
<td>P13</td>
<td>7.9</td>
<td>40</td>
<td>4</td>
</tr>
<tr>
<td>P14</td>
<td>2.3</td>
<td>16</td>
<td>8</td>
</tr>
</tbody>
</table>

Determined experimentally
Determined in pre-test interviews
Scatter Plots and Correlations

Prediction equation?
(next slide)

Prediction Equation

\[ y = 3.2739 + 0.1575 x_1 - 0.4952 x_2 \]

\[ R^2 = .9249 \]

Example:
A 35 year-old player who uses a computer 5 hours per day is predicted to take

\[ 3.2739 + 0.1575 \times 35 - 0.4952 \times 5 = 6.3 \text{ hours} \]

to reach the criterion score.
Example (Lag)$^1$

<table>
<thead>
<tr>
<th>Model for MT (ms)$^a$</th>
<th>Fit$^b$</th>
<th>Variance Explained</th>
</tr>
</thead>
<tbody>
<tr>
<td>$MT = 435 + 190 ID_e$</td>
<td>$r = .560$</td>
<td>31.30%</td>
</tr>
<tr>
<td>$MT = 894 + 46 LAG$</td>
<td>$r = .630$</td>
<td>39.80%</td>
</tr>
<tr>
<td>$MT = -42 + 246 ID_e + 3.4 LAG$</td>
<td>$R = .948$</td>
<td>89.80%</td>
</tr>
<tr>
<td>$MT = 230 + (169 + 1.03 LAG) ID_e$</td>
<td>$R = .987$</td>
<td>93.50%</td>
</tr>
</tbody>
</table>

$^a$ LAG in ms, ID$e$ in bits

$^b$ n = 48, p < .0001 for all models


---

Stepwise Linear Regression

- Stepwise linear regression involves using multiple, and often many, predictor variables
- The variables are added one at a time to determine which explains the most variability (highest $r$)
- The variable yielding the highest $r$ is used in a tentative model, then the remaining variables are tested in the same manner
- Process repeated until all variables added to the model
Social Science Example

- Social scientists are often interested in observing and explaining human behaviour (rather than in measuring and predicting human performance).
- Example
  - A research project sought to determine the “probability of replying to an email message” (dependent variable).\(^1\)
  - 12 predictor variables were tested using stepwise linear regression.
  - Some variables had a positive contribution:
    - E.g., email with only one recipient.
  - Some variables had a negative contribution:
    - E.g., emails from close colleagues.
  - Even with 12 variables, the correlation was modest: \(R^2 = .37\).
  - Behavioural variables are, in general, less stable than performance variables, so the correlation is, in this context, good.


Post Script

- Models presented here were of two types:
  - Descriptive models
  - Predictive models
- The “space” for modeling is likely richer and more diverse.
- Below is a Model Continuum Model (MCM).

\[\text{Descriptive Models} \quad \text{Predictive Models}\]

\[\text{Analogy, Metaphor} \quad \text{Categories, Design Spaces} \quad \text{Analytic Statistics} \quad \text{Equations}\]
Thank You