User Modeling –
Cognitive & Physical Models

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Agenda

• User modeling – cognitive models
  – Model Human Processor
  – GOMS
  – Cognitive Complexity Theory
  – Keystroke-level models

• Physical modeling
  – Fitt’s Law
User/Cognitive Modeling

- Idea: If we can build a model of how a user works, then we can predict how s/he will interact with the interface
  - Predictive modeling, predictive evaluation

Modeling Goals

- Goals (Salvendy, 1997):
  1. Predict performance of design alternatives
  2. Evaluate suitability of designs to support and enhance human abilities and limitations
  3. Generate design guidelines that enhance performance and overcome human limitations

Note: Not even a mockup is required
Components

- Model some aspects of user’s understanding, knowledge, intentions and processing

- Vary in representation levels: high level plans and problem-solving to low level motor actions such as keypresses

Differing Approaches

- Human as information processing machine
  - “Procedural models”
  - Many subfamilies and related models

- Human as biomechanical machine

- Human as a social actor in context
  - Situation action
  - Activity theory
  - Distributed cognition
Cognitive Models

1. Model Human Processor

- Consider humans as information processing systems
  - Predicting performance
  - Not deciding how one would act
  - A “procedural” model
    - People learn to use products by generating rules for their use and “running” their mental model while interacting with system

- From Card, Moran, and Newell (1980’s)
MHP Components

- Set of memories and processors together
- Set of “principles of operation”
- Discrete, sequential model
- Each stage has timing characteristics (add the stage times to get overall performance times)

3 Subsystems

- Perceptual, cognitive and motor
  - Cycle times ($\tau$):
    - $\tau_p \approx 100$ ms ("middle man" values)
    - $\tau_c \approx 70$ ms
    - $\tau_m \approx 70$ ms

- Perceptual and cognitive have memories

- Fundamental recognize-act cycle of behavior
  - Contents of working memory trigger actions held in long-term memory
Perceptual System

- Consists of sensors and associated buffer memories
  - Most important memories being visual image store and audio image store
  - Hold output of sensory system while it is being symbolically coded
Cognitive System

- Receives symbolically coded information from sensory image stores in its working memory
- Uses that with previously stored information in long-term memory to make decisions on how to respond

Motor System

- Carries out appropriate response
Principles of Operation

- Set of principles that describe how behavior occurs (based on experimental findings about humans)
  - Recognize-act cycle, variable perceptual processor rate, encoding specificity, discrimination, variable cognitive processor rate, Fitt's law, Power law of practice, uncertainty, rationality, problem space

Applying the MHP

- Example: Designing menu displays
  - 16 menu items in total
  - Breadth (1x16) vs. Depth (4x4)?
MHP: Calculations

**Breadth (1x16):**
- $\tau_p$ perceive item, transfer to WM
- $\tau_c$ retrieve meaning of item, transfer to WM
- $\tau_c$ Match code from displayed to needed item
- $\tau_s$ Decide on match
- $\tau_m$ Execute eye mvmt to (a) menu item number (go to step 6) or (b) to next item (go to step 1)
- $\tau_p$ Perceive menu item number, transfer to WM
- $\tau_c$ Decide on key
- $\tau_m$ Execute key response

Time = $\left((16+1)/2\right) (\tau_p + 3\tau_c + \tau_m) + \tau_p + \tau_c + \tau_m$

**Depth (4x4):**
Same as for breadth, but with 4 choices, and done up to four times (twice, on average):

Time = $2 \times \left((4+1)/2\right) (\tau_p + 3\tau_c + \tau_m) + \tau_p + \tau_c + \tau_m$

Time = 2380 msec

Therefore, in this case, 4x4 menu is predicted to be faster than 1x16.

Related Modeling Techniques

- Many techniques fall within this “human as information processor” model
- Common thread - hierarchical decomposition
  - Divide behaviors into smaller chunks
  - Questions:
    - What is unit chunk?
    - When to start/stop?
2. GOMS

- Goals, Operators, Methods, Selection Rules
  - Developed by Card, Moran and Newell '83
- Probably the most widely known and used technique in this family

Assumptions

- “Expert” is performing UI operations
- Interacting with system is problem solving
- Decompose into subproblems
- Determine goals to attack problem
- Know sequence of operations used to achieve the goals
- Timing values for each operation
Goal

- End state trying to achieve
- Then decompose into subgoals

Operators

- Basic actions available for performing a task (lowest level actions)

- Examples: move mouse pointer, drag, press key, read dialog box, ...
Methods

• Sequence of operators (procedures) for accomplishing a goal (may be multiple)

• Example: Select sentence
  – Move mouse pointer to first word
  – Depress button
  – Drag to last word
  – Release

Selection Rules

• Invoked when there is a choice of a method

• GOMS attempts to predict which methods will be used

• Example: Could cut sentence either by menu pulldown or by ctrl-x
GOMS Procedure

• Walk through sequence of steps
• Determine branching tree of operators, methods, and selections, and add up the times

GOMS: Example

• Menu structure (breadth vs. depth, again)
• Breadth (1x16):
  Goal: perform command sequence
  Goal: perform unit task of the command
  Goal: perform unit task of the command
  Operator: Look at screen, determine next command
  Goal: Execute unit task
  Select: Which method to enter number of command
e.g. IF item # between 1 & 9 THEN use 1-KEY METHOD
  Operator: Use 1-Key Method
  Operator: Verify Entry... etc.

Result: Average Number of Steps = 33
GOMS: Example, cont’d

- Depth (4x4):
- Similar steps, in slightly different order and looping conditions
  - Result: Average Number of Steps = 24

- Comparison: Depth is ~25% faster in this case
  - Card et al. did not specify step length (in time)
  - Assume 100msec/step, then depth is 0.9 sec faster
  - Similar to Model Human Processor results

Application

- NYNEX telephone operation system
  - GOMS analysis used to determine critical path, time to complete typical task
  - Determined that new system would actually be slower
  - Abandoned, saving millions of dollars
Limitations

- GOMS is not for
  - Tasks where steps are not well understood
  - Inexperienced users

- Why?

GOMS Variants

- GOMS is often combined with a keystroke level analysis
  - KLM - Keystroke level model
  - Analyze only observable behaviors such as keypresses, mouse movements
  - Low-level GOMS where method is given
  - Assumes error-free performance
KLM Characteristics

- Operators:
  - K: keystroke, mouse button push
  - P: point with pointing device
  - D: move mouse to draw line
  - H: move hands to keyboard or mouse
  - M: mental preparation for an operation
  - R: system response time

- Tasks split into two phases
  - Acquisition of task - user builds mental rep.
  - Execution of task - using system facilities

Procedure

- How KLM works
  - Assigns times to different operators
  - Plus: Rules for adding M’s (mental preparations) in certain spots

- Chart on next slide
<table>
<thead>
<tr>
<th>Operator</th>
<th>Description and remarks</th>
<th>Time (sec)</th>
</tr>
</thead>
</table>
| **K** | **PRESS KEY OR BUTTON.**  
Pressing the shift or control key counts as a separate key operation. Time varies with the typing skill of the user. The following shows the range of typical values: | 0.9 |
| Best typist (130 wpm) | 0.12 |
| Good typist (90 wpm) | 0.33 |
| Average skilled typist (55 wpm) | 0.28 |
| Average non-secretary typist (40 wpm) | 0.50 |
| Typing random letters | 0.75 |
| Typing complex codes | 1.20 |
| Worst typist (unfamiliar with keyboard) | 1.55 |
| **P** | **POINT WITH MOUSE TO TARGET ON A DISPLAY.**  
The time to point varies with distance and target size according to Pfitz’s Law, ranging from 8 to 1.5 sec, with 1.1 being an average. This operator does not include the (2 sec) button press that often follows. Mouse pointing time is also a good estimate for other efficient analog pointing devices, such as joysticks (see Chapter 7). | 0.43 |
| **H** | **HOME HANDS ON KEYBOARD OR OTHER DEVICE.** | 0.43 |
| **D**) | **DRAW 8 STRAIGHT-LINE SEGMENTS OF TOTAL LENGTH L CM.** | 9.99 | 0.33 |
| This is a very restricted operator; it assumes that drawing is done with the mouse on a system that constructs all lines to fall on a square, . . . . | 0.15 |
| **M** | **MENTALLY PREPARE.** | 1.35 |
| **R**) | **RESPONSE BY SYSTEM.**  
Different commands require different response times. The response time is counted only if it causes the user to wait. | 1 |
Example

Move Sentence
1. Select sentence
   Reach for mouse        H 0.40
   Point to first word   P 1.10
   Click button down     K 0.60
   Drag to last word     P 1.20
   Release               K 0.60
   Total time            3.90 secs

2. Cut sentence
   Press, hold ^
   Press and release 'x' or Press and hold mouse
   Release ^
   Move to “cut”
   Release

3. ...

Example of KLM

- Breadth menu (1x16)
  - M: Search 16 items
  - 1 or 2 K: Enter 1 or 2-digit number
  - K: Press return key

  Time = M + K(first digit) + 0.44K(second digit) + K(Enter)
  (Look up values, and when to apply “M” operator)
  Time = 1.35 + 0.20 + 0.44(0.20) + 0.20 = 1.84 seconds

Note: Many assumptions about typing proficiency, M’s, etc.
Also ignores most of the time spent determining which task to perform, and how to perform it.
Example of KLM, cont’d

• Depth menu (4x4)
  – M: Search 4 items
  – K: Enter 1-digit number (no M, since expert user)
  – K: Press return key
  Time = M + K(Digit) + K(Enter)
  Time = 1.35 + 0.20 + 0.20 = 1.75 seconds

• Compare the various models in terms of times and predictions:
  – Vary in times, but not in performance predictions

Other GOMS Variants

• NGOMSL (Kieras)
  – Very similar to GOMS
  – Goals expressed as noun-action pair, eg., delete word
  – Same predictions as other methods
  – More sophisticated, incorporates learning, consistency
  – Handles expert-novice difference, etc.
3. Production Systems

- IF-THEN decision trees (Kieras & Polson ’85)
  - Cognitive Complexity Theory
  - Uses goal decomposition from GOMS and provides more predictive power
  - Goal-like hierarchy expressed using production rules
    - if condition, then action
    - Makes a generalized transition network
- Very long series of decisions
  - Note: In practice, very similar to NGOMSL
  - Bovair et al (1990) claim they are identical
  - NGOMSL model easier to develop
  - Production systems easier to program

4. Grammars

- To describe the interaction, a formalized set of productions rules (a language) can be assembled.
- “Grammar” defines what is a valid or correct sequence in the language.
- Used to determine the consistency of a system design
Task Action Grammars (TAG)

- Payne & Green (1986, 1989)
- Concentrates on overall structure of language rather than separate rules
- Designed to predict relative complexity of designs
- Not for quantitative measures of performance or reaction times.
- Consistency & learnability determined by similarity of rules
Modeling Problems

• 1. Terminology - example
  – High frequency use experts - cmd language
  – Infrequent novices - menus
  – What’s “frequent”, “novice”? 

• 2. Dependent on “grain of analysis” employed
  – Can break down getting a cup of coffee into 7, 20, or 50 tasks
  – That affects number of rules and their types
  – (Same issue as task analysis)

Modeling Problems (contd.)

• 3. Does not involve user per se
  – Don’t inform designer of what user wants

• 4. Time-consuming and lengthy

• 5. One user, one computer model
  – No social context
Lower Level Models

- More physically-based
  - Human as biomechanical machine

- Fitt’s Law
  - Models movement times for selection tasks

- Basic idea: Movement time for a well-rehearsed selection task
  - Increases as the distance to the target increases
  - Decreases as the size of the target increases

Model Description 1

- Move from START to STOP

  \[ ID = \log_2 \left( \frac{2A}{W} \right) \]

- Index of difficulty
• **Index of difficulty**

\[ ID = \log_2 \left( \frac{2A}{W} \right) \]

Both quantities are distances so unit-less result.

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**Model Description 2**

• **MT - Movement time**

\[ MT = a + b \times ID \]

MT is a linear function of ID.
**Exact Equation**

- Run empirical tests to determine $a$ and $b$ in $MT = a + b*ID$
- Will get different ones for different input devices and ways the device is used

**Common Equation**

- $MT = a + b \log_2 (A/W + 1)$
- Provides useful numbers
Questions

• What do you do in 2D?

• Where can this be applied in user interface design?

Video

• IBM keyboard pointing stick
Upcoming

• Descriptive Cognitive Models
  – Social context

• Evaluation
  – Experimental design
  – Data collection
  – Subjective measures
  – Data analysis