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Kumon Machine: Learning Math with Silicon Paper

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1. Introduction

This is a proposal for a research project at Washington University to develop a prototype pen-based computer system for evaluating the technological feasibility of a computerized math curriculum for K-12, i.e., the feasibility of a mechanization of the Kumon Math Method[1]. The funding of the project started in January 1991 and the project is expected to end in June 1995.

Learning math involves syntactic learning (computation skills) and semantic learning (concepts and problem solving). Syntactic learning is to learn mathematics as a formal science. Semantic learning is to learn applications of mathematics. Integration of the two is fundamental to effective math education. In American schools children learn mainly mathematical concepts. Syntactic learning is often left for home and calculators. Without sufficient training in computation skills, algebra and calculus become formidable subjects for children in secondary schools. Without algebra and calculus, no technological society can survive. Learning and teaching math is labor intensive and mechanization would ease the problem. However, a successful mechanization of math education requires two essential ingredients; a well-structured curriculum and computer technology for a natural user interface. Children need the teacher's help when the progression of the curriculum is not in synch with the children's pace. Learning math is not equivalent to learning how to use computers. Computers should not be visible to children when they learn math. Today's school math curricula and conventional computer technology are not an adequate basis for mechanization of math education.

There exists a very successful math curriculum for syntactic learning, called the Kumon Math Method. It was developed thirty five years ago in Japan. Kumon is a supplementary, self-learning program individualized for children from preschool through high-school. It consists of roughly 5000 worksheets for line drawing, numeral writing, arithmetic, algebra, and calculus. The goal of the Kumon Method is to make learning calculus as comfortable as possible for every child. It concentrates on development of computational skills necessary to master calculus. No manipulatives and very few word problems are included. Kumon is studied by more than one and a half million Japanese school children. In the USA about fifty thousands students study Kumon. It is taught by franchised Kumon instructors at local Kumon centers. Kumon students bring in their homework to a Kumon center twice a week for review and normally stay in class for 15 to 30 minutes. Required daily homework is not expected to exceed 20 minutes for the lower grade children. Proficiency of the student is defined by his/her ability to work with ease, speed, and accuracy.

In spite of its success in other countries, one obstacle against the successful use of Kumon in the USA is the fact that the Kumon Method is labor intensive. It is labor intensive not only for students but also for parents and instructors. Parents are required to check answers and to manage students' work. Kumon instructors must double check the students' work and make judgements

1 Thomas H. Fuller, Jr. *The Kumon Approach to Learning Mathematics: An Educator's Perspective.* Technical Report WUCS-91-49, Department of Computer Science, Washington University in St. Louis, December 1991.

about the progress of the students. In Japan the required labor is provided by the hidden labor force consisting of the college educated housewives, as Kumon instructors and 'education-mothers'. In the United States, there is no such hidden labor force. Computerization of the Kumon Method, i.e., a design and implementation of the *Kumon Machine*, is a natural solution to the problem.

Existing computer systems are inadequate for the computerization of the Kumon Method. The user-interface through a CRT, keyboard, and mouse cannot emulate the principal paradigm of the method, i.e., a pencil and paper. The unique feature of this paradigm is the very tight feedback loop between the eye, pencil tip, and display on the paper, while the feedback loop between the eye, CRT display, and mouse is not so tight. The development of computational skills, particularly the skills of arithmetic operations, is largely training of hand-eye coordination, and the mouse and CRT do not provide a proper tool for such training. Recently, however, several new technologies have emerged that encourage the computerization of the Kumon Method. The most prominent ones are

silicon paper (pen computing) technology,
smaller size/large capacity disk storage,
neural network technology for character recognition,
expert system,
voice signal processing technology, and
visual language design technology.

The Kumon machine needs an LCD display of size at least 15 cm by 21 cm with 72 dpi resolution, and a wireless light-pen to select an arbitrary pixel precisely and accurately. The Kumon machine also needs handwritten character recognition capability at least for numeric fonts. The new back-propagation learning algorithm gives hope that the construction of such capability in a portable computer system is achievable. The high capacity hard disk makes it economically feasible to select and display on-line any worksheet from the library of 5000 worksheets. The expertise of Kumon instructors is estimated to be representable by an expert system consisting of less than 500 rules. Multimedia communication capabilities are indispensable in educational computer applications. In particular real time speech processing, e.g., speech compression, must be incorporated. The command and control language for the Kumon machine must be a user-friendly, icon-driven visual language such as the Show and Tell Language[2]. The integration of these technologies into a portable personal computer system will be the key to the successful construction of the Kumon machine. Particularly the silicon paper technology will be the central component of the Kumon Machine.

The CRT/mouse interface is currently the dominant technology for interactive computer usage. However, it is not a natural interface for two reasons. First, the feedback control loop of

2 Kimura, T.D., Choi, J.W. and Mack, J.M. "Show and Tell: A Visual Programming Language," Invited paper in *Visual Computing Environments*, E.P. Glinert (ed.), IEEE Computer Society Press Tutorial, Washington, D.C., 1990, pp397-404.

hand, mouse, CRT screen and eye is not tight. Secondly, the mouse is difficult to control. It is controlled by shoulder, elbow, wrist and hand. The portion of the brain used to control these body parts is very small compared with those for hands and fingers. The silicon paper interface, using a flat display combined with a pen-like pixel selector, takes advantage of the dexterity of hands and fingers. It simulates the paper/pencil paradigm[3,4]. It is easy to use. Some commercial products based on this technology are already on the market.

The goal of this research is to evaluate the technological feasibility of a computerized math curriculum for syntactic learning, i.e., a mechanization of the Kumon Math Method. In the process of evaluation, we expect to make scientific discoveries in the areas of user interfaces, visual programming languages, neural networks, and math education.

2. Expected Usage of Kumon Machine

We expect three different modes of using the Kumon Machine (KM) in the future; either at Kumon centers, at regular school classrooms, or at home. The proposed KM prototype should be able to serve in all three modes without major adjustments or modifications. However, the delivery mechanism for the instructional material, e.g. worksheets, will be different from one mode to another.

2.1 Floppy Disk based Kumon Machine

This mode is the traditional way of teaching the Kumon Method. Kumon students come to a Kumon center twice a week for review and exchange of their worksheets. Under this scenario the students are given a KM from the center when they enroll. The Kumon instructor prepares a floppy disk containing a set of worksheets to be completed by each student at home in the week. The student returns the disk to the center after one week's work with additional information on the disk about student's performance during the week. The Kumon instructor also uses a KM at the center to review and monitor the student's work, to duplicate worksheets from the master file to the student's floppy disk, and to update the student database. Based on the student's record, the expert system incorporated in the KM is capable of making a suggestion to the instructor as to how the student should proceed in the following week. The master file of the instructional material is contained in a hard disk at the center's KM.

2.2 LAN based Kumon Machine

This mode is expected to become common in the USA. Schools purchase a number of KMs and a Host Machine (HM, an extension of KM with a large hard disk). Each KM is connected to

3 Kimura, T.D. "Silicon Paper and A Visual Interface for Neural Networks," *Proceedings of 1990 IEEE Workshop on Visual Languages*, Chicago, IL, October 1990, pp. 241-246.

4 Kimura, T.D. "Potentials and Limitations of Pen-Based Computers," Panel session chiarman's position paper, *Proceedings of 21st ACM Annual Computer Science Conference(CSC'93)*, Indianapolis, February 1993, pp. 536 - 537.

the HM through a local area network (LAN). The HM keeps the material master file and the student database. The school designates one of their teachers as the Kumon instructor of the school and the instructor is responsible for maintaining and managing the HM. Students come to a KM everyday to work on pre-assigned worksheets during or after school hours. Each worksheet is transferred on demand from the HM to the KM on line through LAN. The Kumon office regularly updates the material master file of the HM and offers counselling to the Kumon instructor of the school.

2.3 CD-ROM based Kumon Machine

This mode is also expected to become popular in the future. A family owns a KM for home education. All children of the family share the same KM. The entire set of Kumon worksheets are available in a single CD-ROM. Each child of the family keeps the records of Kumon study on his/her own floppy disk. The family may sign up for on-line service from a local Kumon center or a regional Kumon office. Through the fax/modem communication port of the KM, the Kumon instructor has direct access to the study records on the floppy disk, and also has the capability of modifying the study plan initially constructed by the KM's expert system.

3. Functional Requirements

The functionality of KM can be divided into the following four major management areas:

3.1 Instruction Manager

This is the most critical function of KM. It manages administration of Kumon instruction and daily exercises. It consists of:

- Administration of diagnostic tests
- Construction of study plan
  - Starting point
  - Number of worksheets per day
  - Average repetition rate
- Administration of daily exercises
  - Presentation of worksheets
  - Registration of starting time
  - Audio encouragement/warning
  - Grading
  - Registration of finishing time
  - Recording score points
  - Decision of review vs. advancement
- Administration of completion tests
- Construction of problem sets

- Remedial
- Advanced

° Selection and presentation of semantic information

- Student initiative
- Instructor initiative
- Parents initiative

3.2 Database Manager

There are four different types of databases the Kumon Machine has to manage:

° Main worksheets in CD-ROM

5A, 4A	8MB (20KB x 400)
3A - D	2.4MB (2KB x 1200)
Answers	

° Auxiliary multimedia hypertexts (semantic information) in CD-ROM

- Explanations in hypertexts
- Illustrations by bitmap images
- Narrations by synthesized voice
- Suggestions by animation

° Student records on floppy disk

- Name, birthdate, grade, school, starting date
- Parent's name, address, phone, occupation
- Daily exercise
    - date, starting time, finishing time
    - starting level, finishing level
    - number of errors
- Monthly summary
    - total number of worksheets, actual advancement, repetition rate

° Kumon statistics in CD-ROM

- Average progress charts
- Case studies

3.3 Communication Manager

KM's communications with a Kumon instructor or a Kumon office are carried out through a high-speed modem in the fax form or in the textual form with voice compression capabilities. The format and the protocol of such communications must be managed for proper and timely reporting of student's performance. It consists of:

° Hand-shaking with remote machine

- Fax/Ascii modem

° Interpretation of remote queries on worksheets and student's performance

- Daily data

Monthly data

Remote learning through fax

- Scheduling of reporting obligations

    Dialing

    Journaling

- Production of reports

    Maintenance of report forms

3.4 Interface Manager

This manages the dialogues between Kumon students and the KM. It is the second most important function of KM, next to Instructional Management. Since KM will be used by a wide range of students, young and old, the machine interface has to be extremely user friendly. There are three major strategies for the user-friendliness of KM; handwriting, multimedia, and visual programming. Interfacing with handwriting is one of the most natural communication modes for school children. A combination of textual, pictorial, and auditory communication makes a man-machine communication similar to human communication. A visual programming language is intuitive and easy to understand. A single visual programming language will be introduced in place of a traditional job control language, a device control language, a database query language, and a procedural programming language.

The Interface Management functionality consists of:

- Editing

    Drawing tools

    Text Editor

- Browsing

    Databases

    Commands

- Recognition of handwriting

    Numeric fonts for worksheets

    Alphabetic fonts for commands

- Recognition of simple voice commands

    Noise level detection

    Start/Stop commands

- Interpretation of commands expressed in a visual programming language

    Device control

    Data query

    Procedure specification

- Presentation of hypertexts

    Bitmap images

    Animation

    Graphs and texts

- Generation of synthesized voice
    - Encouragement
    - Warnings

4. System Configurations

In order to satisfy the above functional requirements, we propose to develop a prototype system consisting of three layers; hardware, firmware, and software. The first two layers provide a platform suitable for pen-based computer systems, that is comparable to Macintosh operating system including some of Toolbox routines.

4.1 Hardware

The principal components are as follows:

CPU	68030 (25MHz)
ROM	512KB
RAM	8MB
DSP	DSP56001 (20MHz)
CD-ROM	600MB
Display	640 x 400 (with digital tablet)
Floppy	4MB (2")
Serial port	1
Parallel port	1
SCSI	1
Speaker	1
Microphone	1
Keyboard	optional

4.2 Firmware

The firmware consists of two major components, operating system kernel and toolbox routines. The operating system kernel provides multi-tasking capability for real-time control of hardware devices. The toolbox extends the operating system facilities. Its purpose is to provide general software tools useful for constructing application software for silicon-paper based computer systems.

The following modules are available from ROM:

Operating System Kernel:

- Preemptive Scheduler for Multitasking
- Device Drivers
- Event Queue Manager
- I/O Control System
- Clock Manager

Toolbox:

- Draw Manager
- Expert Shell
- Hyperflow Manager
- Fax Manager
- Sound Manager
- Script Manager
  - Gesture Recognition
  - Character Recognition
  - Text Editor

4.3 Software

Corresponding to the four areas of functional requirements, the software configuration is also divided into four major modules.

- Instruction Manager
  - Expert system
    - for review/advancement
    - for selection of semantic information
    - for study plan construction
- Database Manager
  - Worksheet Database
  - Hypermedia Database
  - Student Records Database
  - Kumon Statistics Database
- Communication Manager
  - Remote Learning
  - Monthly Report
  - Fax Protocol
  - Host-Target Protocol
- Interface Manager
  - Browser
  - Editor
  - Macro Definitions
  - Voice Synthesis

5. Research Components

Successful completion of this project requires a satisfactory resolution of the following three technical problems:

° Improvement of the display technology.

The current LCD display technology needs improvement in the area of enhancement of contrast, brightness, higher resolution, and reduction of parallax. We expect a significant progress to be made hardware manufacturers in this area during the next five years.

- Handwritten character recognition.
  The real time recognition and training of multiple source handwriting with the recognition rate of 95% is still to be achieved. We propose to solve the problem with neural network simulations by high speed DSP capabilities.

- Development of a new user interface paradigm
  Silicon paper technology requires a new paradigm of user interface to replace the window/menu paradigm. We propose a new model called Hyperflow as the KM user interface.

6. Statement of Work

In order to achieve the goal of automating the Kumon Method, we propose to construct a prototype Kumon Machine by performing the following tasks in four phases in collaboration with the sponsor. In the first Research phase, we propose not only to evaluate commercially available platforms for pen-based computer systems but also to prototype our own platform, so that we may secure, at the end of Phase 2, the best platform possible for the Kumon Machine.

6.1 Evaluation of operating systems and hardware platforms (Task 1)

We will evaluate operating systems that are designed for silicon paper technology and are available or soon will be available on the market, for their adequacy for the Kumon Machine implementation. Each candidate operating system will be evaluated in terms of:

Universality
Performance
Ease of Use
Development Status
Handwritten Character Recognition Capability

The final product of this task will be documented recommendations to the Kumon Institute on possible hardware systems as a basic platform for the Kumon Machine.

6.2 Hardware design and prototyping (Task 2)

As a back-up for the task 1, we will design and develop our own basic platform for the Kumon Machine. The platform will consist of a single-board MC68030 based computer system and the kernel of a real-time operating system with multi-tasking capability. Tentative candidate for OS is OS9 of Microware.

6.3 Development of handwritten character recognition capabilities (Task 3)

We will continue our efforts to construct a character recognition system based on the neural network technology. It is expected that the capabilities of gesture recognition, numeric character recognition, and simple voice recognition will be integrated into one module in the script manager of the toolbox routines. This task will be carried out as a part of research projects pursued at the Center for Intelligent Computer Systems (CICS).

6.4 Design of expert systems for Kumon instructions (Task 4)

In order to automate the Kumon Method, it is essential to construct expert systems that embody the expertise and experiences of Kumon instructors. We will investigate efficient methods of implementing the following three expert systems in the Instruction Manager module:

Decision of review/advancement based on speed and accuracy,

Selection of semantic information relevant to the current worksheet,

Construction of study plan for an individual student.

The task will consist of two parts;

(1) construction of expert shell, and

(2) construction of a set of rules for each expert system.

The first part of this task will be carried out as a part of CICS research activities, and the results will be incorporated into the toolbox that resides in ROM. The second part will be incorporated into the Instruction Manager and will reside in RAM.

6.5 Toolbox design and implementation (Task 5)

In this task we will develop software tools that are useful for constructing application software for silicon-paper based computer systems. Our toolbox will consist of six components:

Draw Manager, a collection of graphics routines,

Expert Shell, an interpreter of expert rules,

Hyperflow Manager, an extension of Show and Tell interpreter,

Fax Manager, an interpreter for the fax communication protocol,

Sound Manager, audio and voice synthesizers, and

Script Manager, a recognizer for gestures and handwritings.

In designing Hyperflow Manager, we will continue our efforts that started with the Show and Tell project five years ago, to develop a new computer interface paradigm for novice users. Hyperflow Manager covers capabilities offered by Window Manager, Control Manager, and Menu Manager of Macintosh. The Fax Manager contains a fax-modem simulation algorithm for the DSP chip. Similarly, the Sound Manager contains a voice synthesizer algorithm for the DSP chip. The Script Manager integrates user's interactions with the Kumon Machine, either through gesturing, handwriting, drawing, or through keyboarding, into one uniform sequence of events. In case a commercial operating system is selected at the end of Phase 1, we expect that it will contain the Draw Manager and Script Manager components, but not the other four components.

6.6 Requirements analysis and specifications (Task 6)

In this task the Kumon Method will be analyzed thoroughly. The task involves analysis of:

Kumon worksheet

Kumon instruction

Kumon center management

Kumon business needs.

This task will be performed in consultation with one Kumon expert assigned by the Kumon Institute to this project who will be located at the Department of Computer Science, Washington University in St. Louis. The expert is expected to assist the project team on the overall Kumon Method in general and on Kumon worksheet in particular.

The final product of the task will be the specification of requirements for the Kumon Machine. It may include the possible addition/modification of Kumon worksheet.

6.7 Software system design and implementation (Task 7)

This task involves design and implementation of:

Instruction Manager

Database Manager

Communication Manager

Interface Manager

Documentation of user manuals and system manuals.

For Interface Manager, a visual programming language will be designed for the Kumon Machine as its language for job control and data query. Hyperflow will be used as the base language.

The software system will be developed by using the rapid prototyping methodology. We will develop three prototype versions without sharing code, in principle, among them. Each developmental cycle consists of design, implementation, and evaluation. User manuals and system manuals will be produced concurrently with the final prototyping cycle.

This task will be performed in consultation and collaboration with two system programmers assigned by the Kumon Institute to this project who will be located at the Department of Computer Science. The purpose of this collaboration is (1) to provide additional manpower for system implementation and (2) to transfer software technologies necessary for the Kumon Institute to maintain the software system developed during the project.

The final product of this task will be a software system that is ready for field testing.

6.8 Performance evaluation based on field testing (Task 8)

We will evaluate the performance of the prototype system for the Kumon Machine through controlled adaptation at selected Kumon centers and schools. It involves:

Experiment design for observing the strengths and weaknesses of the Kumon Machine

Interviews with Kumon students and parents as end users

Interviews with Kumon instructors as end users

Interviews with Kumon administrators as end users

Curriculum design for school adaptation of the system

Teacher education on the Kumon Machine

Administration of classroom experiments.

This task requires participation of two education experts to assist the project team in administration of classroom experiments and to evaluate the field operations of the prototype machine.

The final product of this task will be a final report of the project summarizing results of the performance evaluation and recommendations for future actions.

7. Progress Status

As of march 1993, the first version, based on the 68030-based custom-made hardware, was completed and tested in September 1992. The second version is currently under development on the PenPoint operating system with EO-880 as the hardware platform.