Issues Arising from the Design and Construction of a Paper Computer

Michael Goodwin
Lecturer, IT Department, Otago Polytechnic
MikeG@tekotago.ac.nz

Dr. Samuel Mann
Associate Professor, IT Department, Otago Polytechnic
smann@tekotago.ac.nz

Abstract

This paper discusses various approaches attempted in the design and construction of a functioning computer to be constructed from paper. The purpose of this exercise was to develop a working model that could be printed and handed out at presentations, to be cut out for assembly. The primary aim is to create an easily distributed, durable educational aid whose assembly by the recipient reinforces understanding of both its function and its functionality. Other aims include focussing of public awareness on sustainability issues in computing, and also provision of a novel advertising medium for the research itself. The primary component considered was a binary counter, controlled by user input to count up and down. Carrying of binary digits on addition, and borrowing on subtraction were both to be incorporated, as were an addition overflow flag and a subtraction underflow flag. It is anticipated that as many binary counter modules as possible could be chained together to manage manipulation of large binary numbers, with the strength of the paper being the limiting factor in this chaining. Design and mechanical issues arising from the limitations of the medium are described, as are solutions found and problems remaining.

Keywords: Computing education, sustainability

1 Introduction

The purpose of this work was to investigate the feasibility of constructing a working binary counter out of paper. This is to comprise the first of a range of paper constructs related to computing concepts, under the name “Cut-out Computer” (Mann, Goodwin *et al.* 2007.) Other planned paper constructs range from Boolean Logic Gates to Web 2.0 Social Constructs.

The aim of the Cut-out Computer project is to provide a set of educational constructs to demonstrate important concepts in computing, in the form of printouts that can be handed out at presentations and seminars. These can then be cut out, assembled and operated by attendees, with both the assembly and the operation giving educational insight into both the computer-related concept modelled by the construct, and the method by which the concept is actually implemented in a functioning computer.

This Supplementary Proceedings paper appeared at the *21st Annual Conference of the National Advisory Committee on Computing Qualifications* (NACCQ 2008), Auckland, New Zealand. Samuel Mann and Mike Lopez (Eds). Reproduction for academic, not-for profit purposes permitted provided this text is included. www.naccq.ac.nz

The main purpose of selecting paper as the main medium for the Cut-out Computer project is for convenience of delivery and local impact, with minimal requirements for production. In particular, paper provides a suitable medium for delivery at public events, needing only the provision of a printer, and possibly a computer-controlled paper cutter.

This selection is also of relevance with respect to sustainability issues in computing, by providing a permanent use for the material as a user-assembled, functioning educational aid and demonstration model. Furthermore, pure paper models in the Cut-out Computer range could be distributed electronically if required.

Design of the binary counter would have been markedly less challenging if more flexible materials had been used, but the distributable quality of these would have been impaired.

2 Literature Review

2.1 Use of Mechanical Computers in Education

The literature describing the use of paper and other mechanical computers as educational aids in themselves, is much sparser than that covering education of the history of mechanical computers per se (Impagliazzo *et al.* 1999.) There are, however, some interesting antecedents to the current research.

An early example of usage of a fictional mechanical computer for educational purposes is (Anno 1973), where Dr. Stone Brain Computer (alternately translated as “Hard-headed Calculator”) discusses computer-related concepts with his children friends, giving them his insight from the point of view of a functioning computer, culminating in a discussion of human-robot relationships.

The Billiard-Ball Computer is a theoretical mechanical computer (Fredkin and Toffoli 1982) where the transmission and processing of digital signals is modelled by the motion and interaction of billiard ball-type objects. For example, an AND gate is modelled by means of a cavity into which billiard ball-style signals are injected. The shape of the cavity, together with the collision dynamics of the signals, defines the output in an appropriate manner, as illustrated in Figure 1 (Wikipedia 2008.)

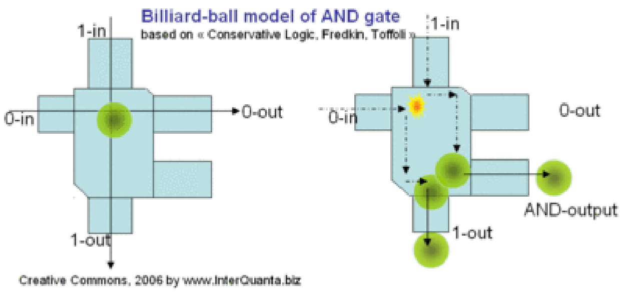

Figure 1: Billiard Ball Computer implementation of an AND gate

Classical mechanics techniques enable the Billiard Ball Computer model to be used to explore areas of theoretical interest in computability. Furthermore, consideration of systems with large numbers of billiard ball-type objects allows techniques from classical thermodynamics to be used in information theory.

A similar, if less academic, mechanical computer is the Domino Computer (Johnston 1999), where data signals and their processing are modelled by lines of standing dominoes on a board, together with intersections of lines designed to knock each other over in such a way as to model the corresponding digitally processed output. Interestingly, some problems in the implementation of Domino Computer logic echo those found in the research at hand.

A related project is Bell's Unplugged (University of Christchurch New Zealand 2008) where, rather than mechanical computers being used for education, learning activities for Information Technology are developed for use in the absence of any computer systems.

2.2 Inspirations for the Paper Computer

A number of items provided inspiration and initial guidance in outlining our research.

An early introduction to mechanical computer construction is (Warring 1970), where the construction from wood of a decimal counter (and a pre-decimal British Sterling currency counter) is described.

An example of the explanation and construction of an intricate mechanism from paper is (Smith Rudolph 1984.)

A number of amusing and educational paper-based automata have been designed by (Ives 2007.)

An invention with a similar aim to the current research is (Wandel 2007), where binary addition is modelled using marbles as set binary digits, travelling through intersecting wooden channels, and deflected by two-state wooden toggles.

3 Methodology

3.1 Constraints of the Medium

For maximum delivery impact, we decided that the printed template should fit on a single sheet of 160gsm A4 card. Colour printing allows for addition of construction tab labels and assembly and operating instructions, as well as a range of colour schemes. We planned to include cut-lines and score-lines to facilitate assembly, by processing the printed cards on a recently acquired Robotech CraftRobo paper cutter.

Our aim was for the template to be simple to construct - ideally less complicated than the concept illustrated.

We wished to minimise any use of ancillary components apart from scissors (in the absence of the CraftRobo) and glue. However, we did consider such components as drinking straws, elastic bands, and retracting pen springs.

The pliability and softness of paper card precluded any mechanisms that depend overly on the precision of finished parts.

3.2 Design to Follow Function

For didactic purposes, we aimed to design the paper binary counter in such a way that its construction and functioning were evocative of the actual functionality of a real binary counter. Considered aspects included:

- Implementation of digital concepts by digital mechanisms, rather than relying on coincidentally analogous behaviours of the continuous paper media. For example, the speed with which a binary digit changes state should not change with the module's value position (in contrast: with simple, analogue 2:1 gearing, each gear wheel rotates half as fast as its predecessor in the gear train.)
- The nature of possible counting trigger mechanisms (single finger press; application/return of lever to initial position; rotation of trigger wheel.)
- Visibility of the mechanisms in action.

3.3 Binary Counting Concepts

From an educational perspective, we felt that a deeper than usual investigation of the concepts involved in binary counting would be have benefit.

The fundamental concept in binary processing is the two-state mechanism, corresponding to OFF (0) and ON (1.)

The next most important concepts that arose in our effort were those of carrying a digit (in the case of binary addition) and borrowing a digit (in the case of binary subtraction), whereby individual binary digits interact with their neighbours.

We also came to realise the need to express the concepts of not carrying and not borrowing, in the cases where a change in value of a binary digit does not affect its neighbours.

3.4 Stages of Development

3.4.1 The Flapper

The original inspiration for the work described here was the Flapper (Lopez and Mann 2007), as illustrated in Figure 2. This is a chain of S-shaped card counter pieces that rotate around a wire shaft. As each counter piece rotates, its wings interfere with neighbouring pieces, which are thus dragged round in a fashion that carries along the chain in a binary counting fashion.

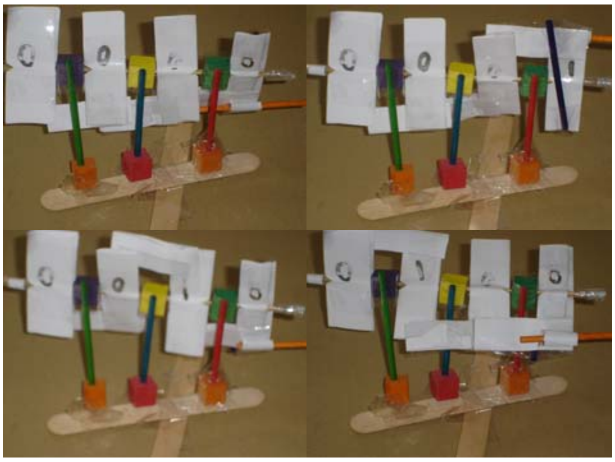

Figure 2: Mike Lopez's Flapper, showing incrementing of binary digits as it is rotated

3.4.2 Hexaflexagons

Another early inspiration for possible binary counter mechanisms was the hexaflexagon (EnchantedLearning.com, 2007), as illustrated in Figure 3. The plans for this were discovered during a search for models suitable for printing and cutting on the CraftRobo paper cutter. The original purpose was to print advertising material for Otago Polytechnic ICT Department, for distribution at a public presentation, and it was felt that the four-state rotation of the unit, combined with the fact that a single display face is visible at any one time, would lend the design to adaptation as a binary counter.

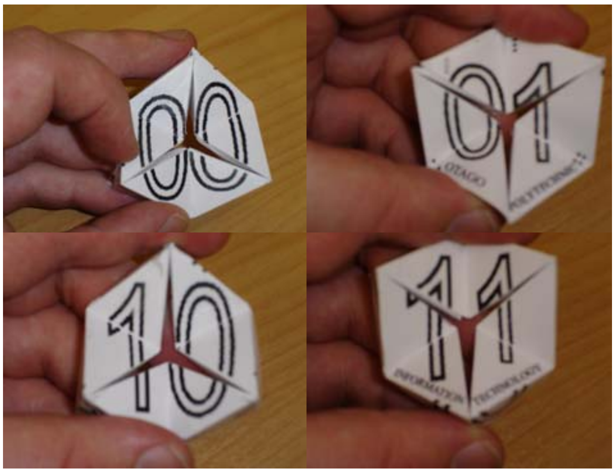

Figure 3: The Hexaflexagon, which is a triangular-faceted torus that can roll around itself

3.4.3 Push-Pull Binary Blocks

Our first custom attempt to construct a binary counter consisted of push-pull binary blocks, as illustrated in Figure 4; each module of which has a cubic main body to house the binary digits to be controlled. The intention was that an array of modules could be housed in a casing with fixed apertures to display the correct binary digit for each module

Attached to one side of the module's main body is an extension to act as a pusher to control the neighbouring higher-value digit module when a binary addition triggers a carry operation. At the end of the extension is a protuberance to act as a hook to control the same neighbouring module when a binary subtraction triggers a borrow operation.

The space between the main body and the protuberance is for incorporation of a clutch mechanism, to disengage control of the neighbouring block during a don't-carry or don't-borrow operation.

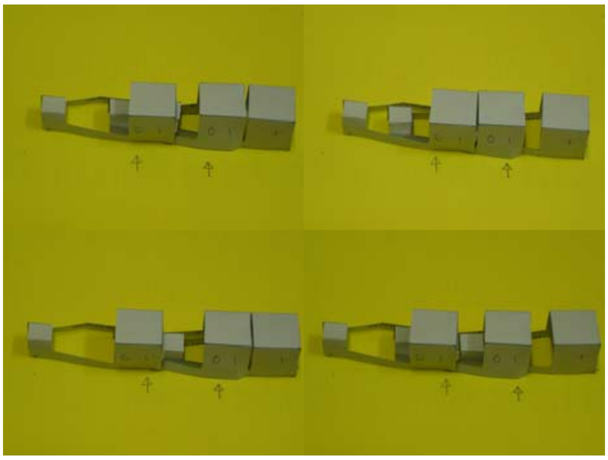

Figure 4: Push-Pull Binary Blocks – a very early prototype showing the required binary counting sequence, but with no clutch mechanism yet in place

3.4.4 Binary Gears

At the time of writing, our latest binary counter model is composed of binary digit display gearwheel modules that are interconnected by "half-gears", which have their teeth stripped for half of their circumferences. These half-gears are co-axial with fully toothed driver gears, as illustrated in Figure 5.

This transmission method was designed to ensure that the driven module is either moving at the same speed as the driving module, or not at all.

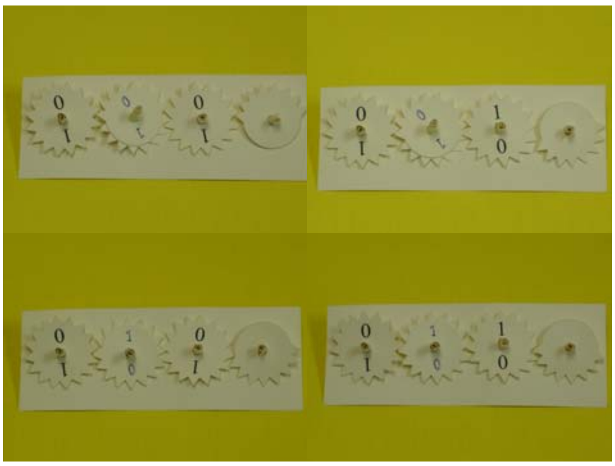

Figure 5: Binary Gears, showing successive disengagement each half-turn; the third binary digit's half-gear is obscured by its lower-valued neighbour's transmission gear, which is co-axial

4 Results

4.1 Constraints of the Medium

Although we felt that our identified constraints were not unduly harsh, we have not yet succeeded in developing a paper binary counter to our satisfaction. Each developed mechanism breaches one or more of our conditions, and we have thus far failed to combine correct functionality with our initial aims of educational construction and an educational mechanism.

4.2 Design to Follow Function

The majority of our binary counter models so far have fallen into the trap of relying on (analogue) rotational mechanisms to model the cyclic two-state nature of binary digit changes. It is not yet clear that this is the best solution.

In review, we have not yet managed to identify a preferred binary counting trigger mechanism.

We have succeeded (in each working case) in making visible the mechanism of our binary counters; whether this visibility adds educational value to the product is not yet clear.

4.3 Binary Counting Concepts

We feel that we have arrived at a more granular level than before of understanding of the component mechanisms of binary counters. This is of relevance in an educational context, but we have not yet integrated this understanding into a suitable paper model.

The two-state mechanism concept has been carried through in our research, but as we progressed we found that the correspondence between the (mechanically symmetrical) pair of states and their conventional values (OFF/ON) became obscured, leading to some confusion as to how to trigger control of the binary counter. We have reached the stage where we have a number of triggering mechanisms from which to select.

We have incorporated the concepts of triggering state changes in neighbouring modules to implement carry and borrow operations. Initial models' behaviour was limited to control of next highest-value neighbouring module for binary addition; although technically more complex, the extension of this to next lowest-value neighbouring modules for binary subtraction is mechanically similar.

The passive operations of don't-carry and don't-borrow are not generally considered, but have been found to be important in this context, requiring a clutch mechanism to disengage neighbour control in these cases.

4.4 Stages of Development

4.4.1 The Flapper

The Flapper neatly shows a two-state switch. It also illustrates the binary counting concepts of carrying and borrowing digits, and it could in principle be adapted to illustrate counting overflow and underflow events.

Drawbacks of the Flapper from the point of view of the research at hand centred on the fact that it required major non-paper components. These included a stiff wire framework, both as a rotation shaft and as supporting rods, and retaining elastic bands to prevent the counter pieces from windmilling.

Reliable operation of the Flapper is limited, as the strength required to push higher-value digit flaps past their adjacent support rods is too great to be transmitted by lower-value digit counter pieces. These tend to flap out of turn instead.

Variations of the Flapper were built, including one with a zigzag rotation shaft, but these displayed similar shortcomings. Further variations were considered, such as with cam grooves on a paper tube shaft, to move the counter pieces axially to control intermeshing, but these would have required a stiffer construction medium.

4.4.2 Hexaflexagons

Some problems were encountered in laying out the parts of the binary digits to be printed on non-neighbouring hexaflexagon surface facets, due to the fact that the net used was not composed of exactly equilateral triangles. These were overcome, and the resulting unit elegantly shows a limited binary sequence (00-11), but the hexaflexagon has a number of disadvantages:

- There is no notion of process – the unit can be rolled around continuously or reversed at will, with no counting trigger to instigate the action, and no usage or illustration of the mechanisms of carrying or borrowing of digits.
- It is not feasible to incorporate illustration of overflow or underflow handling – use of one of the four available faces to illustrate such a condition would limit display to just three binary states, and use of two faces to differentiate between an overflow and an underflow would limit display to just two states, which we considered insufficient to demonstrate the concept.
- This solution is not scalable – it is conceivable that more complex, higher-order flexagons could be constructed, but these would each still have an inherent counting limit, irrespective of the strength of material. Furthermore, higher-order flexagons would presumably become less convex, meaning that the frontal binary count display would be more difficult to discern.

Whilst working on the printing alignment of the binary counter hexaflexagon, the authors discovered a dichotomy in personal style with respect to flexing the resulting unit. One author thought that the other had ordered the binary numbers to descend rather than ascend. This turned out to be because they felt it more natural to flex the unit inward from the top, whereas the person who selected the ordering felt it more natural to turn the unit outward. An informal survey of Otago Polytechnic IT Department staff found that approximately 30% of respondents preferred the inward method, with no obvious correlation between turning style and handedness, gender, age or course subjects taught, but with a marked preference in every case.

Since experimenting with hexaflexagons as binary counters, a computer-based application has been discovered for generation of their illustrated nets for printing (SourceForge.net, 2008).

4.4.3 Push-Pull Binary Blocks

A suitable concept clutch mechanism for implementation of carrying and borrowing has not yet been established for the push-pull binary blocks. Initial thoughts centred on a flat block to be rotated to stand proud in the clutch gap to engage the neighbouring block in the case of a carry operation, and to lie flat in the case of a don't-carry operation.

However, a simple, visible mechanism for gearing clutch rotation to counter triggering has not yet been identified. We came to realise that any viable such mechanism could be suitable in its own right as a binary counter (leading to the concept of the binary gears), with the blocks becoming extraneous.

It was also uncertain whether this mechanism is scalable to the case where a borrow operation is required to trigger a non-adjacent module, to borrow through one or more binary zeroes.

4.4.4 Binary Gears

This mechanism does work as a binary counter, and could be made scalable by unitising the modules and their driver gear assemblies. The stripped halves of the half-gear wheels act by default as disengagement clutches.

However, the binary geared binary counter does have a number of failings as an educational construct. Whilst the net for a three-module counter does fit on an A4 sheet of paper card, the mechanism requires a rigid base and tightly housed axles, neither of which is ideally constructed from this medium.

As an educational aid, we feel that the binary gears mechanism is overly complex, and not particularly illustrative of the concept being implemented. This is because it relies on analogue rotation to trigger digital binary counting, and on complex and obscured full/half driver wheel units to implement carrying and clutch disengagement.

The current prototype also suffers the drawback of not representing two symmetrical states to illustrate the concept – we found that the half-gear teeth clashed on declutching, causing the driven module to precess slightly ahead of its correct position for display. This was ameliorated by stripping an extra tooth, but a fully symmetrical solution would require either smaller teeth (which is infeasible on grounds of available precision), or larger gear wheels (which would result in the model no longer fitting on a single sheet of card.)

5 Conclusion

We have created a number of models for educational binary counter constructs from paper card. These are functionally correct to varying degrees, and we believe they are suitable in a didactic setting to varying degrees. However, we have not yet combined these two requirements into a single model to our satisfaction.

During our research, we have gained a more detailed and explicit understanding of the concepts involved in implementation of a practical and illustrative binary counter. Furthermore, we have applied a number of different mechanisms to apply these concepts.

Other mechanisms currently under consideration include ratchet wheels and rack-and-pinion systems. We also plan to examine the use of a retracting pen mechanism as a two-state machine (controlled by a circular ratchet acting as clutch), provided we find a way to manage the asymmetry between extension and retraction in this case. Furthermore, it would be preferable that the retracting pen mechanism could be adapted to not require a spring.

We are now confident that we can select and combine suitable constructs to build a paper binary counter that meets our guidelines, and look forward to extending our work further, into other Cut-out Computer concepts.

6 References

Anno, M. (1973) *My Good Friend: the Stone Brain Computer*. Tokyo, Diamond

EnchantedLearning.com: *Make a 3-D Hexaflexagon*. http://www.enchantedlearning.com/math/geometry/hexaflexagon/instructions.shtml. Accessed 5 Nov 2007

Fredkin, E., Toffoli, T. (1982): Conservative Logic. *International Journal of Theoretical Phyics* **21**:219-253.

Impagliazzo, J., Campbell-Kelly, M., Davies, G., Lee, J. and Williams, M. (1999): History in the Computing Curriculum. *Annals of the History of Computing* **21**(1):4-16

Ives, R.: *Flying Pigs Limited*. http://www.flyingpigslimited.com/. Accessed 28 Mar 2008

Johnston, D. (1999): *The Computer/Domino Connection*. http://www.pinkandaint.com/oldhome/comp/dominoes/index.html. Accessed 12 May 2008

Mann, S., Goodwin, M., et al. (2007). Poster: *Works Just Like Clockwork: Model Making For Teaching Computing Concepts*. 20th Annual Conference of the National Advisory Committee on Computing Qualifications, Nelson, New Zealand, NACCQ in cooperation with ACM SIGCSE. 277pp

Smith Rudolph, J. (1984): *Make Your Own Working Paper Clock*. London, Harper Collins.

SourceForge.net: *Hexaflexagon Toolkit*. http://hexaflexagon.sourceforge.net/. Accessed 8 Jun 2008

University of Canterbury, New Zealand: *Computer Science Unplugged*. http://csunplugged.com/. Accessed 5 May 2008