6.4 Digi Island: A Serious Game for Teaching and Learning Digital Circuit Optimization

Digi Island: A Serious Game for Teaching and Learning Digital Circuit Optimization

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Abstract. Karnaugh maps, also known as K-maps, are a tool used to optimize or simplify digital logic circuits. A K-map is a graphical display of a logic circuit. K-map optimization is essentially the process of finding a minimum number of maximal aggregations of K-map cells with values of 1 according to a set of rules. The Digi Island is a serious game designed for aiding students to learn K-map optimization. The game takes place on an exotic island (called Digi Island) in the Pacific Ocean. The player is an adventurer to the Digi Island and will transform it into a tourist attraction by developing real estates, such as amusement parks and hotels. The Digi Island game elegantly converts boring 1s and 0s in digital circuits into usable and unusable spaces on a beautiful island and transforms K-map optimization into real estate development, an activity with which many students are familiar and also interested in. This paper discusses the design, development, and some preliminary results of the Digi Island game.

1.0 INTRODUCTION

Electronic games are a pervasive aspect of American culture and entertainment: as many as 65 percent of American households play games [1]. With a revenue of $20.2 billion in 2009 [2], the game industry has evolved into an important sector that is larger than the film industry. The passion for games can be exploited for more vital purposes, such as education, training, and marketing, via "serious games." Game-based learning uses serious games with defined learning outcomes and objectives. The values of game-based learning have been recognized by organizations such as National Science Foundation and National Research Council [3-5]. NSF considers games as an important form of cyberlearning platform and technology [6]. The latest ground-breaking game technologies, such as Nintendo Wii and Microsoft Kinect, have significant impact on gamers, transforming gameplay into a more positive and healthy experience. Now the gamer demographics cover every age group [1].

Digital circuits are embedded in almost all electronic equipment and devices in use today, such as computers, MP3 players, and digital cameras. Digital circuit optimization, or simplification, is a process to reduce the complexity of the digital circuits so that electronic devices will have a smaller size (thus less weight) and less power consumption (thus prolonged battery life). Various techniques have been developed in the last several decades for digital circuit optimization. Among them, the Karnaugh map is the standard method to teach digital circuit optimization in introductory digital circuit courses because its graphical representations facilitate logic simplification, providing an intuitive and systematic way for circuit optimization. However, many students have difficulties learning circuit optimization using Karnaugh maps merely because it is the first time for them to be exposed to Karnaugh maps and class lectures do not provide enough coverage and exercises. A serious game that exploits students' interest and curiosity with games would be helpful for learning circuit optimization using Karnaugh maps.

As part of a Senior Design Project at the Department of Electrical and Computer Engineering of Old Dominion University, the authors developed a serious game, Digi Island, to aid teaching and learning digital circuit optimization using Karnaugh Maps. This paper discusses the design and development of the game and presents some preliminary results.

2.0 BODY

2.1 Digital Circuit Optimization Using K-maps

There are two different types of electronic circuits: analog circuits and digital circuits. Analog circuits represent and process information in continuous or analog form, while in digital circuits, information is represented and processed in discrete (most commonly binary) forms. Most components of modern electronic devices are digital circuits and the transformation from analog to digital is still underway. Use the media for storing music as an example. The traditional audio cassette tapes store music as analog signals, while the MP3 music players that became extremely popular in the last decade store music as digital signals. Compared with analog systems, digital systems have many advantages in terms of flexibility, programmability, computational capability, numerical accuracy, information storage and retrieval, error detection and correction, and miniaturization [7].

The same logic function can be implemented by different digital circuits with varied complexities. Thus, it is necessary to find the optimal digital circuit with minimum complexity for the desired function. Such process is called digital circuit optimization or simplification, which is important to reduce the size and weight of electronic devices and prolong their battery life (just think about the evolution of cell phones since their inception in terms of size, weight, and battery life). Circuit optimization is an important theoretical concept covered in introductory digital circuit courses. Various techniques have been developed in the last several decades for digital circuit optimization, including Boolean algebraic manipulation and minimization, Karnaugh maps, Quine-McCluskey, Petrick's algorithm, Espresso, and others [7]. Among them, the Karnaugh map is the standard method to teach digital circuit optimization in introductory digital circuit courses because it is a graphical representation that facilitates logic simplification, providing a standard and systematic way for circuit optimization.

Karnaugh maps, also known as K-maps, are graphical representations of logic circuits, which can also be represented by Boolean algebraic expressions. The sides of a K-map represent circuits inputs, while each cell of a K-map represents the corresponding circuit output with values of 1 or 0. Figure 1 shows a K-map representing a circuit with 4 inputs. K-map optimization is essentially the process of finding a minimum number of maximal aggregations of K-map cells with values of 1 according to a set of rules. Circuit simplification using K-maps requires understanding of several key concepts, including implicant, prime implicant, and essential prime implicant [7-8]. To find the optimized expression of a K-map, all prime implicants must be identified first. The optimized expression is the logic sum of all essential prime implicants and other prime implicants consisting of minterms not included in the essential prime implicants. The remaining nonessential prime implicants can be determined using a selection rule that minimizes the overlap among prime implicants [8]. K-maps are introduced in introductory digital logic circuit courses, such as ECE 241 *Digital Logic Circuit* at Old Dominion University. Without understanding and using K-maps proficiently, students are likely to fail in this introductory course and more advanced digital circuit courses.

AB \ CD	00	01	11	10
00	1	0	0	1
01	0	1	1	0
11	1	1	0	1
10	1	0	0	1

Figure 1 A 4-variable K-map

2.2 Game Design

The goal of the game Digi Island is to provide both a formal introduction to K-maps and an engaging game setting that encapsulates the K-maps. To this end, Digi Island is designed as a construction based strategy game [9-10]. The game has three modes: Tutorial Mode, Practice Mode, and Play Mode. The Tutorial Mode provides several tutorials about the K-map through exemplary circuits with 2, 3, and 4 inputs; it identifies implicants, prime implicants, and essential implicants in these circuits, illustrates the procedure of selecting essential prime implicants and nonessential implicants using the selection rule, and finally generates the Boolean expression for the optimized logic circuit. The Practice Mode first displays rectangles in K-maps with 2, 3, and 4 input variables and asks the player to identify them as implicants, prime implicants, or essential prime implicants. The player needs to find all implicants, prime implicants, and essential prime implicants directly. User interfaces should be provided to start and end identification of these terms. The player also needs to generate the optimized Boolean expression. User interfaces should be provided to the player to enter input variables, their complements, and the logical OR operation. Both the Tutorial Mode and Practice Mode provide instructions and practices using standard representations of K-maps that are used in regular classrooms.

The Play Mode is the fun part of the Digi Island game. There are no more K-maps in the Play Mode and instead the player sees a beautiful island (called Digi Island) in the Pacific Ocean. In the game, the player is an adventurer to the Digi Island and will transform it into a tourist attraction by developing real estates, such as amusement parks and hotels. However, not all places can be exploited by the player, such as rocks and reserves for wild lives. The player is given a map of Digi Island that labels all usable and unusable spaces. Large buildings bring about better financial outcomes as they provide more efficient utilization of the space. Thus, the goal of the player is to construct a minimum number of building as large as possible covering all the usable spaces, while satisfying the regulations of the Pac Republic, which exercises sovereignty over the Digi Island. Some sample regulations are listed below.

- All the spaces occupied by each building must be adjacent to each other.
- The number of usable spaces (blocks) in each building must be a power of 2.
- Sharing spaces between adjacent buildings is allowed, but should be minimized.

Initially, the player has a certain amount of cash that can be used to exploit the island and construct buildings on the usable spaces. Depending on the importance of the buildings, they have different values and are represented differently, e.g., single house, skyscrapers. Larger buildings are more valuable and generate more profit for the player and thus more points.

In addition to the game design discussed above, the game has a number of other requirements. The game must be deployed and playable on personal computers and Microsoft Zune HD media players. The touch screen of the Zune HDs must be utilized as input device. Sound effects must be included to provide user feedback. Voice instructions should be provided as well.

2.3 Game Development

The development of the game Digi Island contained two major components: front end and back end. The front end mainly contains a graphical user interface that displays menus, tutorials, and K-maps. The front end has different user input modes for K-map manipulation and provides user feedback for their actions. The back end contains the major logic for digital circuit optimization, that is, for an input digital circuit, the back-end generates the optimized Boolean expression, compares that with the player's solution (answer), and provides feedback to the player. In the following, the back end is discussed first.

2.3.1 Logic Circuit Optimization

Since the goal of the game is to help the player learn logic circuit optimization using K-maps, the game must know the final optimized Boolean expression for an input logic circuit. Although K-maps are effective visual tools used by humans for manual circuit optimization, they are not suitable to be implemented on computers for automatic circuit optimization. Several other logic circuit optimization algorithms have been developed and here we mainly discuss two widely used methods: Espresso algorithm and Quine-McCluskey algorithm.

The Espresso algorithm is the de facto industry standard for circuit optimization and it was initially created by Brayton et al. [11] and later revised by Rudell of University of California at Berkeley [12]. The Espresso algorithm is a heuristic but effective algorithm in terms of memory usage and computational complexity. Although it does not guarantee to produce an optimized circuit, in practice it always leads to a solution that is either optimal or very close to optimal. The source code of the Espresso algorithm in C programming language is available for downloading from the University of California at Berkeley [13]. There were several options to utilize the Espresso algorithm in the game: 1) porting the Espresso C source code to C# in the game, 2) compiling the source code into libraries and calling the libraries in the game, and 3) calling the executables of Espresso directly. Considering the time restriction (only one semester) of this senior design project and that the Espresso is a complex algorithm, it was not feasible to port the Espresso source code in C to C# in this project. Options 2 and 3 worked for the game running on the personal computers (PCs), but didn't for the game on the Zune HD player since there is no C compiler that can generate object code for the Zune HD platform. Considering these obstacles, the Espresso algorithm was not deemed suitable for this project.

The Quine-McCluskey algorithm is another widely used method for circuit optimization [14-15]. The Quine-McCluskey algorithm is designed to work similarly to the human brain's pattern recognition. It is a systematic method that guarantees to produce the optimized Boolean expression and its tabular form makes it suitable for computer implementation. The Quine-McCluskey algorithm first finds all implicants with *n* variables, then combines some of them to implicants with *n* - 1 variables, and continue this combination process until all prime implicants are found. The algorithm then identify all essential prime implicants using a prime implicant chart. However, the circuit is not fully optimized or minimized yet as the remaining prime implicants may still have overlap. A covering procedure is then utilized to select a minimum number of remaining non-essential prime implicants in the prime implicant chart so that the circuit function is fully covered. Unlike the Espresso algorithm, No authoritative source code exists for the Quine-McCluskey algorithm. Since it is a systematic method that is straightforward to implement, the team decided to develop the C# code for the Quine-McCluskey algorithm from scratch. The Microsoft .NET Framework and C# programming language were utilized to develop the code. C# is an object-oriented programming language drafted by Microsoft and has been approved as a standard by ISO.

2.3.2 Game Play

Microsoft XNA Game Studio is a game development toolkit for Windows, Xbox 360, Zune HD players, and Windows phones. The XNA Game Studio consists of two parts: XNA Framework and a set of tools and templates for game development. The XNA Framework is an extensive set of libraries for game development based on the Microsoft .NET Framework. It encapsulates low-level technical details so that game developers can focus more on content and high-level development [16]. XNA provides templates for common tasks, such as development of games, game libraries, and game components. It also provides utilities for cross-platform development, publishing, and deployment. Developers can make use of both the XNA Framework and the .NET Framework in the game with the former for game-specific tasks such as graphics rendering and managing inputs and latter for more general programming tasks.

XNA Game Studio is a powerful tool for rapid development of cross-platforms and it was selected as the tool to implement the graphical user interface and game play. XNA Game Studio 3.1 was used and the latest version is 4.0 Beta. Object oriented programming (OOP) was utilized and a number of classes were developed to represent different game scenes, graphical user interface, user inputs, K-map, and logic circuit optimizations. XNA Game Studio provides a fundamental class Game that handles game logic update and drawing. A class diagram of the game is shown in Figure 2.

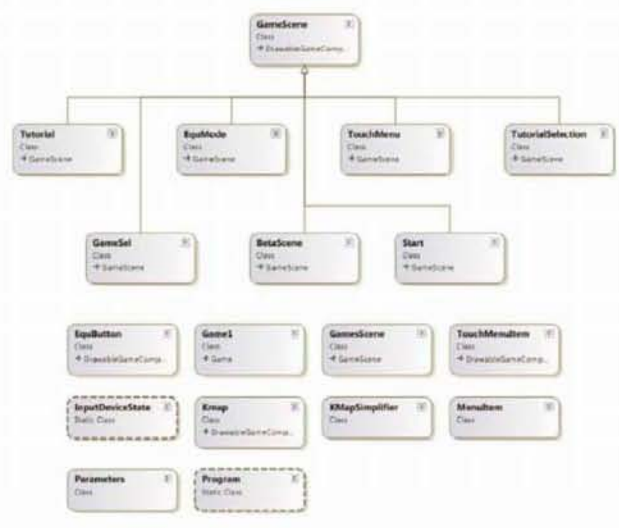

Figure 2 A class diagram of the game.

2.4 Preliminary Results

A preliminary prototype has been developed as a product of this Senior Design Project in the Spring Semester of 2010. Some screen captures of the game are shown in Figure 3.

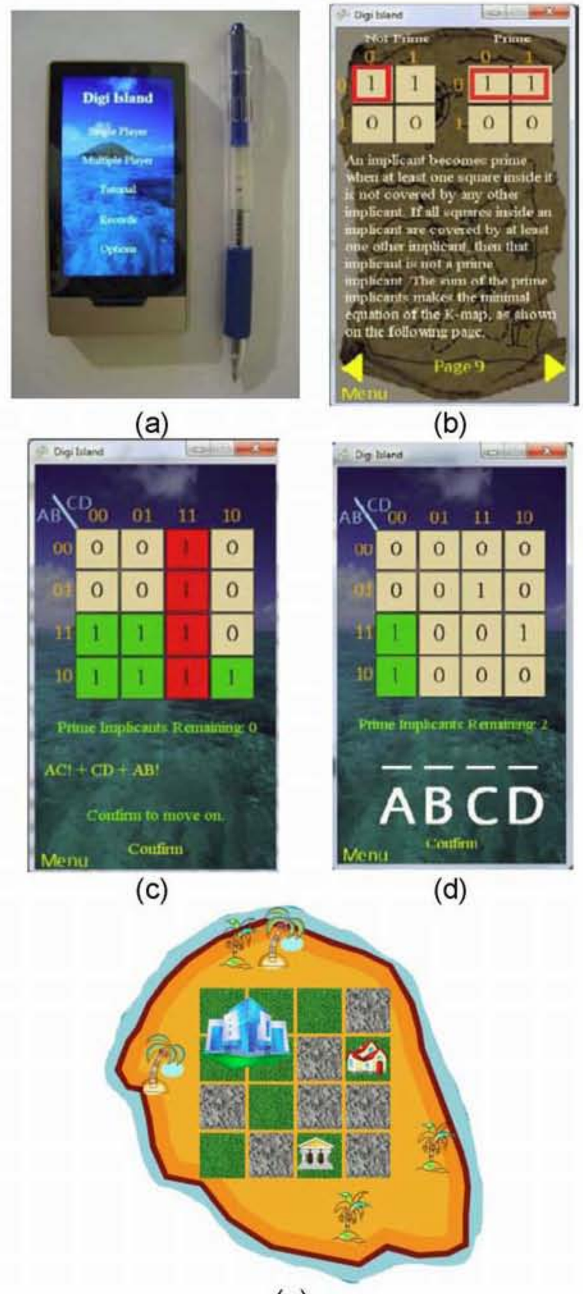

Figure 3 Screen captures of Digi Island. (a) Welcome screen. (b) Tutorial. (c) Practice mode with direct implicant selection. (d) Practice mode with equation input. (e) Play mode.

The game has been deployed on the Zune HD media player, Figure 3(a); it has a multimedia tutorial, Figure 3(b); the player can select different input mode (direct implicant selection and equation input) to enter the answer, Figure 3(c); the Digi Island map is shown in Figure 3(d).

3.0 DISCUSSION

The limited prototype of the game already demonstrated many advantages of the game. For example, the typical K-maps in the textbooks contain many overlapping rectangles representing different primary implicants, making them visually confusing and difficult to understand. In the Digi Island game, each primary implicant can be selected and highlighted individually through user interactions, leading to a much clearer representation and better understandings. Advanced rendering techniques, such as transparency control using alpha maps, can be used to align two K-maps to facilitate groups of minterms, which is not possible using just plain textbooks or paper and pencil methods.

One important principle of learning is to connect new concepts and understanding to pre-existing knowledge [17]. The *Digi Island* game elegantly converts boring 1s and 0s in digital circuits into usable and unusable spaces on a beautiful island and transforms K-map optimization into real estate development, an activity with which many students are familiar and also interested in. The rules for K-map optimization exhibit themselves as construction regulations for real estate development. Players will be more engaged when they deal with real assets such as skyscrapers and amusement parks rather than blocks of abstract 1s and 0s.

Currently, the K-maps are randomly generated by the game and the player has no control of the K-map generation. In the near future, we will add another mode in which the player can generate his/her own K-maps. However, this may have some unintended effects, e.g., the player can use this game to solve homework problems. An area of future development is to include "don't cares" in the K-maps, which are the outputs of certain inputs that do not matter. They "don't cares" can be treated as either 1 or 0. Usually including the "don't cares" in the K-map optimization can further simplify the circuit.

The game can be further expanded to have multiplayer mode to form more competitive and engaging game plays. Players can face off against each other to see who can solve a K-map the fastest. With networking, a game server can also be setup to store player configuration and performance. The game can be easily ported to smartphones using Windows Phone 7 with very minimal effort.

4.0 CONCLUSION

K-maps are an important tool for teaching and learning digital circuit optimization and simplification, which is critical to reduce physical size and power consumption of electronic devices and prolong their battery life. This paper discussed the design and development of Digi Island, a serious game for teaching and learning K-map optimization. The game was developed as a product of a senior design project at Old Dominion University. The Digi Island is a fun and engaging game that offers many advantages over traditional teaching methods of K-maps and it will be further expanded and enhanced in the near future.

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9/13/2010 1

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Outline

- Introduction
- Digital Circuit Optimization Using K-maps
- Game Design
- Game Development
  - Logic Circuit Optimization
  - Game Play
- Results
- Discussion and Conclusion

9/13/2010 2

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Digital Circuits and Optimization

- Digital circuits are present in almost all electronics equipment and devices today
  - Computers, MP3 players, digital cameras, etc.
- Optimization of digital circuits reduces complexity.
  - Less weight, longer battery life

9/13/2010 3

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Necessity of Optimization

- Same logic function can have multiple solutions of varying complexities.
- Necessary to find the solution that has the least complexity.
- Reduction in complexity allows for reduction in weight and size of circuits, and increase in battery life.
- Process to find the least complex circuit is known as digital circuit optimization.

9/13/2010 4

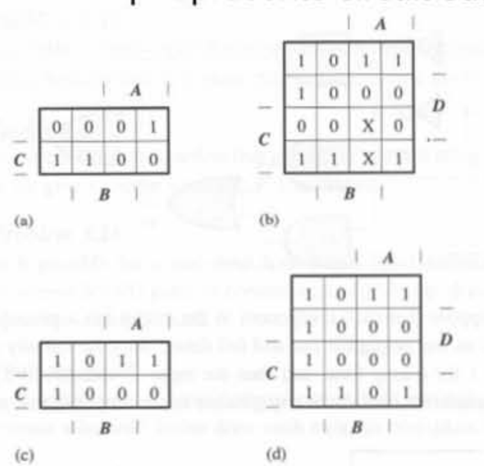
Methods of Optimization

- Various methods of optimization have been developed over the years.
  - Boolean algebraic manipulation and minimization
  - Karnaugh maps
  - Quine-McCluskey algorithm
  - Espresso algorithm
  - Petrick's algorithm
- Karnaugh Map is the standard method for teaching digital circuit optimization.

9/13/2010 5

Karnaugh Map Overview

- Karnaugh maps (K-maps) graphically represent logic circuits intuitively and systematically.
- Sides of a K-map represent circuit inputs.
- Each cell of a K-map represents circuit output with values of 1 or 0.



9/13/2010 6

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K-map Optimization (1/2)

- K-map optimization is the process of finding a minimal number of maximal aggregations of K-map cells.
  - Cells must have a value of 1.
  - Grouped according to a set of rules
- Key concepts to understanding K-maps
  - Implicant
  - Prime Implicant
  - Essential Prime Implicant

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K-map Optimization (2/2)

- To find the optimized expression, identify all prime implicants.
- Optimized expression is the sum of essential prime implicants and prime implicants not contained in essential prime implicants.
  - Remaining prime implicants determined by selection rules
  - Selection rules minimize implicant overlap.

Digi Island Overview

- Passion for games can be exploited for educational purposes via "serious games."
- Goal of the game is to formally introduce K-maps in an engaging manner.
- Designed as a construction based strategy game.
- Digi Island has three modes
  - Tutorial Mode
  - Practice Mode
  - Play Mode

Game Requirements

- Must be playable on personal computers and the Microsoft Zune HD.
- On the Zune, the touch screen is the input device.
- Sound effects and voice instructions must be included.

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Tutorial Mode

- Provides several tutorials by providing circuits with 2, 3 or 4 variables.
- Identifies implicants, prime implicants and essential implicants.
- Illustrates procedure for selecting prime implicants and nonessential implicants.
- Generates final Boolean expression for the circuit.

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Practice Mode

- Displays K-maps with 2, 3 or 4 variables.
- Asks the player to identify implicants, prime implicants and essential prime implicants.
- Player needs to find all implicants directly.
- Player must also generate the optimized Boolean expression.

Play Mode

- Play mode is where Digi Island evolves from a teaching tool to a fun, engaging game.
- Player is an adventurer to Digi Island, and challenged to develop the island into a tourist attraction by developing real estates.
- Player cannot utilize the entire island.
  - Rocky terrain
  - Wildlife preserves
  - Regulations from the local government
- Player must maximize available space with buildings to produce the greatest income.

Game Components

- Game development contained front end and back end components.
- Front end component deals with graphical user interface.
  - Menus, tutorials, K-maps
  - Different user input modes and user feedback
- Back end component contains major logic for digital circuit optimization.
  - Generates optimized Boolean expression(s)
  - Compares possible solutions to player's answer

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Logic Circuit Optimization

- To effectively teach students about K-maps, the game must know the final optimized expression.
- K-maps work well visually, but do not lend well to implementation on a computer.
- Several algorithms have been developed for logic circuit optimization.
  - Quine-McCluskey algorithm
  - Espresso algorithm

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Espresso Algorithm

- Heuristic algorithm that is highly efficient
- Doesn't guarantee optimized circuit, but close.
- Available from University of California at Berkeley.
- Not feasible, as implementation options either too time consuming or incompatible with Zune HD.

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Quine-McCluskey Algorithm

- Uses pattern recognition similar to human brain.
- Guarantees optimal solution, but inefficient.
- Team developed code for the algorithm from scratch.
  - Microsoft .NET Framework
  - C# programming language

9/13/2010 17

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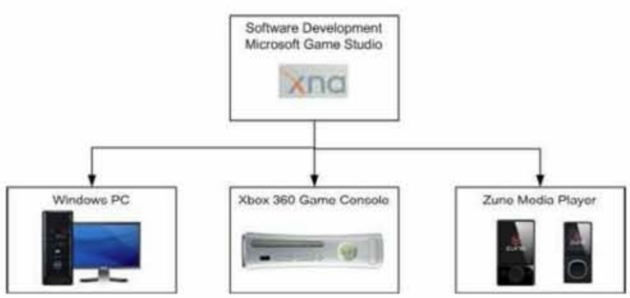
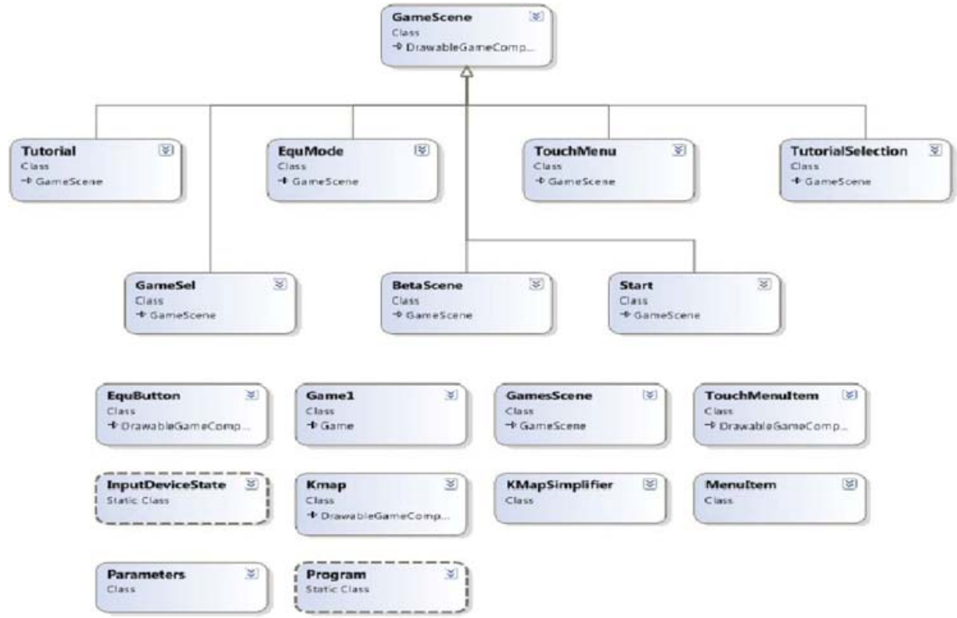
Programming Tools

- Game play developed using Microsoft's XNA Game Studio, which supports cross platform development and includes
  - Tools and templates for rapid game development
  - Optimized libraries based on Microsoft .NET Framework
- XNA Game Studio provides "Game" class to handle game logic updates and drawing.
- Utilized object oriented programming to develop a number of classes.



9/13/2010 18

Class Diagram

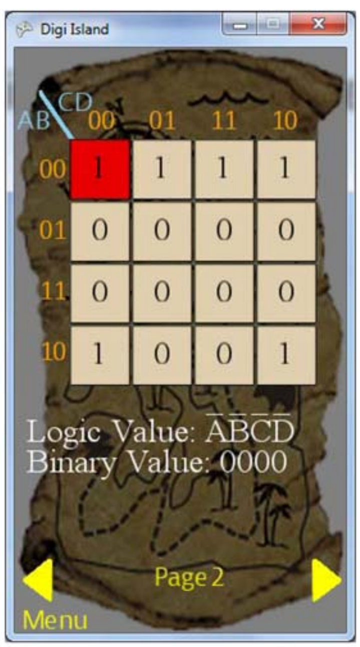


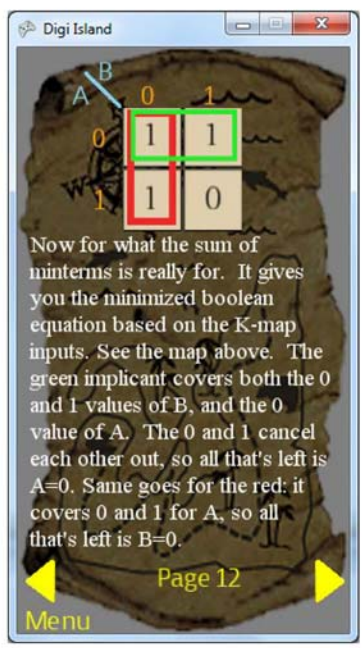
Preliminary Results

- Prototype deployed on the PC and Zune HD.
- Tutorial and practice modes completed, with minor aesthetic changes possible.
- Quine-McCluskey algorithm developed from scratch.
- Play mode yet to be implemented.

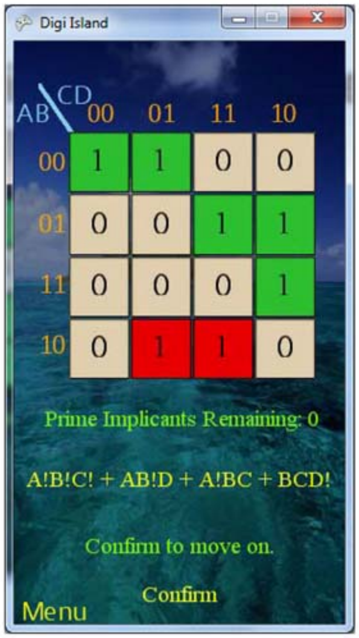
Zune Implementation

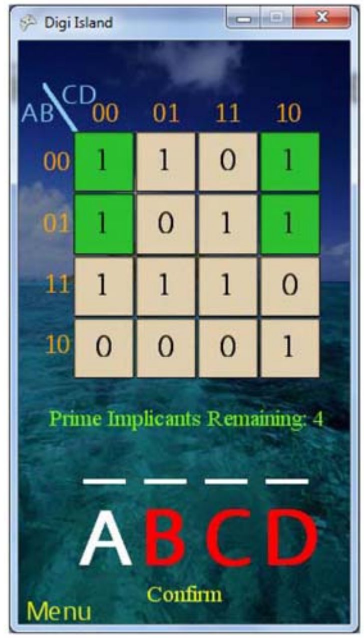
Tutorial Mode





Practice Mode





Advantages of Digi Island

- Textbook examples of K-maps are visually confusing, which renders them difficult to understand.
- Digi Island allows users to highlight specific answers, leading to clearer understanding.
- Digi Island converts K-maps into an island that players transform to earn points, which engages learning.

Future Developments

- Include “Don’t Cares”, or outputs that do not matter and can be either 0 or 1.
- Multiplayer mode
- Port to smartphones with Windows Phone 7.

Conclusion

- K-maps are important for teaching digital circuit optimization.
- Digital circuit optimization is necessary to reduce size and increase battery life of circuits.
- Digi Island is a fun, engaging game that offers many advantages over traditional teaching.
- Digi Island will be further enhanced and expanded.

Questions?

Thank you!