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Improving Learning of Digital Systems Concepts Using a Video Game

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Early Studies of a Video Game for Improving Learning of Digital Systems Concepts

Student interest in physical and mathematical sciences and engineering has been steadily declining, and a need to reverse this trend and improve students' STEM education in K12 and college has been cited by a multitude of governmental, independent, and industry organizations[1-3]. At the same time, tremendous growth has occurred in the computer and video game industry, particularly among teenagers. It is now a multi-billion dollar industry, with an annual growth rate that far exceeds the growth of the entire U.S. economy[4]. The Entertainment Software Association[5] reported U.S. computer and video game sales grew from $7.0 billion in 2005 to well over $10.0 billion in 2010.

Despite their appeal to U.S. teens and college students and the identified educational potential of games, adoption rates for educational video games are still very low[6,7]. This is partly due to the lack of empirical evidence of the effectiveness of games as learning environments[7-9], and the lack of literature on how to design, develop, and implement effective games for learning. In 2006, NSF organized a National Summit on Educational Games with the specific objective of discussing "ways to accelerate the development, commercialization, and deployment of new generation games for learning" [9]. Among reasons cited for the U.S. need to focus on digital games for learning, is that video games "require players to master skills in demand by today's employers" (p. 4) – strategic and analytical thinking, problem solving, planning and execution, decision-making, and adaptation to rapid change. They also identified several attributes of video games that are important for learning: clear goals, lessons that can be practiced until mastered, monitoring learner progress and adjusting instruction to learner level of mastery, closing the gap between what is learned and its use, motivation that encourages time on task, personalization of learning, and infinite patience. These are incorporated into an ongoing research project along with other research on computer based learning and what has and has not worked, including its use in student design projects [10-20].

The research project uses a video game, *PlanetK* (see figure 1), as a tool to improve student learning of digital systems concepts which is uniquely tailored to the nature of today's student, who has perhaps been affiliated with video games since childhood and sees them as a part of their teen or college age culture. For the past two decades, researchers have studied learning styles of engineering students in an effort to increase student learning and retention, with findings indicating differences in preferences based on gender and by ethnicity [20], that students of color may encounter problems "when they attempt to adapt their styles to the theoretical, often abstract, reasoning utilized in mathematics and the hard sciences" (p. 7). [21] , and that the learning styles of most engineering students and teaching style of most engineering professors are incompatible [22,23]. These issues and transforming the educational experiences from a mismatch into one of student engagement in learning are addressed in the objectives, questions, and measures of this project.

Figure 1. Screenshot of PlanetK 3D Virtual Environment Scene

These observations and the literature on game-based learning support the notion that games could be used to address several of the issues in engineering education identified earlier. However, given the mixed results of the research on learning through games in particular and on educational technology in general [24], a design-based research (DBR) approach is being used in this project, since it is advocated as a means to overcome shortcomings of existing educational research [26,27]. In DBR, an intervention goes through multiple cycles of design, enactment, analysis, and redesign with the intention of improving the intervention, and gaining insights that can lead to shared theories with implications for designing other interventions [25].

Two objectives of the research project are: (1) create new student learning materials and strategies which vertically integrate a conceptual or pedagogical approach on digital system design into sequences of courses in electrical and computer engineering (ECE) and computer science (CS) curriculums, and (2) contribute to knowledge on undergraduate student attitudes on the use of video games as a motivator for pursuing or persisting in an ECE or CS major, and the effect on student performance, especially those from underrepresented groups. The effectiveness of the game is assessed using a comprehensive array of assessment instruments.

The research plan entails studying the use of the video game in three diverse institutions. Texas A&M University will use PlanetK in three courses: Introduction to Digital Design, Introduction to Engineering, and Digital Integrated Circuit Design, since the game contains different levels that can address the various concepts needed in each course. PlanetK will address digital systems learning objectives in the Introduction to Engineering Course and many learning objectives in the Introduction to Digital Design course, and serve as an introductory module to refresh students on digital design concepts in the Digital Integrated Circuit Design course. Introduction to Digital Design is a sophomore-level course currently taught with lectures and smaller weekly laboratory sections that are led by teaching assistants. Introduction to Engineering is a two credits first semester freshman course that includes lecture and laboratory. When the project began, the Introduction to Engineering course was divided into tracks containing students from similar engineering majors (e.g. electrical engineering, computer engineering, and computer science). The course has been revamped; therefore, an alternative approach for integrating the game into the course will be determined in the future. PlanetK will be implemented in a sophomore-level Logic Circuits course in the ECE department at Prairie View A&M University which teaches digital systems material. Texas A&M University- Corpus Christi will adapt and implement PlanetK in two CS courses that teach digital systems material: Introduction to Problem Solving with Computers, and Computer Architecture. In Introduction to Problem Solving with Computers, students are introduced to the fundamentals of computer science, with digital systems material being taught for three weeks, along with binary numbers, basic Boolean logic, and logic gates. Students are introduced to digital circuit design using Boolean logic, and building adders, multiplexors, decoders, and registers from logic gates; and build an ALU and control unit and a small computer system from the basic block. Computer Architecture students are introduced to basic types of flip-flops, counters, multiplexers, registers and then use them later on for building other blocks of the computer. In this course students become more familiar with designing and building circuits. They are also introduced to various Boolean logic simplification methods like Karnaugh maps etc. Although digital systems material is covered throughout the course, the first five weeks entirely focus on digital systems material.

This paper discusses the implementation of the game and brief results from studies conducted in Fall 2015 and Spring 2016. The following sections of the paper present an overview of the objectives of the research, learning objectives of the video game, and structure of the game. Further the paper discusses brief results of a common pre- and post-tests and evidence-centered embedded assessment in the game.

PlanetK

Two objectives of the research are: (1) create new student learning materials and strategies which vertically integrate a conceptual or pedagogical approach on digital system design into sequences of courses in electrical and computer engineering (ECE) and computer science (CS) curriculums, and (2) contribute to knowledge on undergraduate student attitudes on the use of video games as a motivator for pursuing or persisting in an ECE or CS major, and the effect on student performance, especially those from underrepresented groups.

PlanetK can be utilized in three areas of instruction for targeted courses: laboratory, teaching of fundamental course concepts, and assessment of learning. The utilization of *PlanetK* in the targeted courses will potentially affect learning in several ways. *PlanetK* will provide: 1) an opportunity for students to learn material in an environment that most of them are familiar and comfortable with, but with a different teaching style that is active and visual; 2) an opportunity for students to determine individualized comprehensions of the rules and relationships for the course concepts in a non-sequential way; 3) an opportunity for students to learn complex concepts at their individual pace; 4) students to receive the concrete style of instruction used in laboratory experiences; and, 5) a different mechanism for student demonstration of learning using a style that some students may prefer and feel is fairer than conventional examinations. In theory, positive student attitudes motivate persistence in a major.

The learning/instructional objectives that *PlanetK* will address are listed in Table 1. The game currently only includes the combinational digital circuitry concepts. The game is organized into several Worlds. Each *World* in the game emphasizes a related set of learning objectives, with each World further split into multiple *Levels*, each targeting a smaller set of learning objectives. Within each Level there are multiple *Stages*, each focusing on one subordinate learning objectives. Table 1 shows the mapping of the various Worlds in the game to the learning objectives of the project. Worlds 0-3 have been developed so far. The final Level in each World contains "Star" problems that encapsulate all of the learning objectives for that World. The star problems include design and analysis problems.

Currently a player has to go through the Levels and Worlds in sequence. However, the Stages can be explored in any order. The structure is similar to that found in several role playing games (RPGs) with the "Star" problems representing the final battle with the "boss" challenge (see figure 2). Each world has 2-3 "star problems" which the user must complete in order to demonstrate that they have achieved the learning objectives for that World and to move on to the next objectives (world). This design combines the freedom to explore, which is a key feature of video games, with a sequential progression that is typical to a course of study.

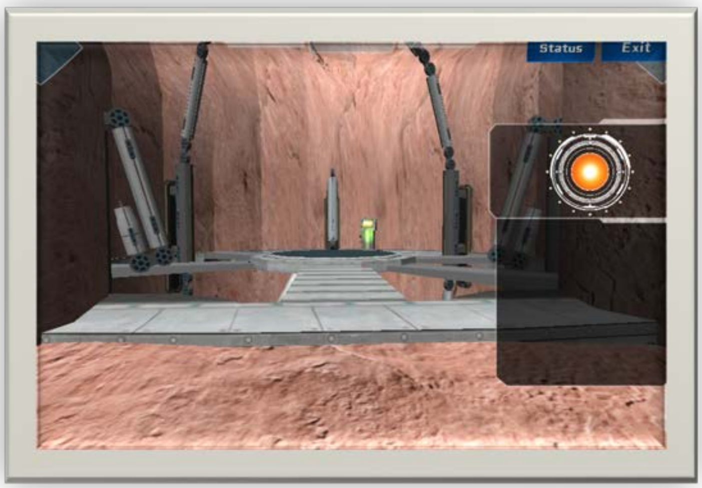

Figure 2 - Screenshot of 3D Virtual Environment Scene from World 2

In the game, digital circuit design problems are presented in the form of truth tables specifying the desired output for the given inputs, boolean expressions specifying the logic expressions representing the function of the problems, or word problems describing the problems. A player can generate design solutions in a circuit environment where they can drag and drop various gates and custom building blocks from an inventory box onto a board that has the external inputs and outputs (see figure 3). Wire connections between the gates and custom blocks, and external inputs and outputs can be made using mouse clicks. Further a player can toggle the input states between logic '0' and logic '1'. The game updates the external outputs automatically to indicate the values of the outputs of the current circuit for the specified input values. The wires are also colored to indicate the logic 0/1 state at the wire inputs. These features allow the player to follow the circuit from inputs to outputs observing what happens for each input combination, providing a circuit debug option. When a player has completed a circuit, he/she clicks a button that invokes a Boolean logic solver which determines if the circuit is equivalent to the truth table, Boolean expression, or word problem. The game visually indicates how many of the truth table combinations the circuit satisfies. If all combinations are satisfied the player has successfully solved the problem. Otherwise the player may attempt to redesign the circuit.

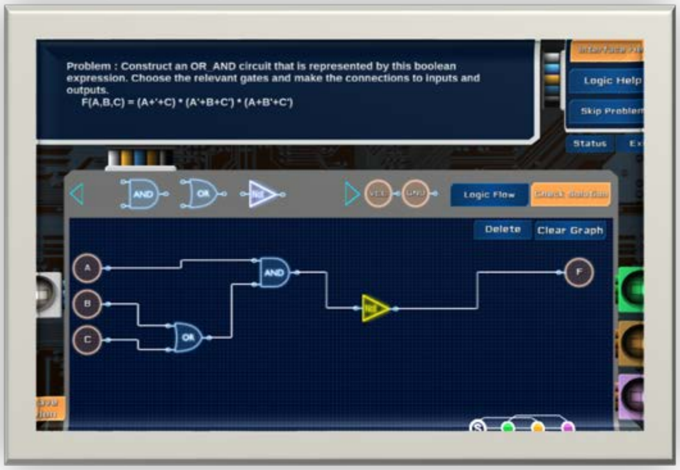

Figure 3 – Screenshot of 2D Circuit Design Environment

The game provides four components that players can use to assist in developing design solutions or when they encounter difficulties. *Interface Help* (see figure 4) explains how to use the features of the digital circuit design components of the game. *Logic Help* provides context-sensitive help for the players about their current game problem while also allowing players to access fundamental material on digital logic that they may need if they have limited prior knowledge. *Logic Flow* provides a scaffold for players to test their design solutions for various input values. Logic Flow provides a color coded circuit bit flow which conveys the bit output value of each logic circuit component between the inputs and outputs of the current circuit design. *K-Map tool* helps players easily create K-Map solutions within the game to simplify their design solutions for game problems. All of the components are under user control, providing just-in-time usage.

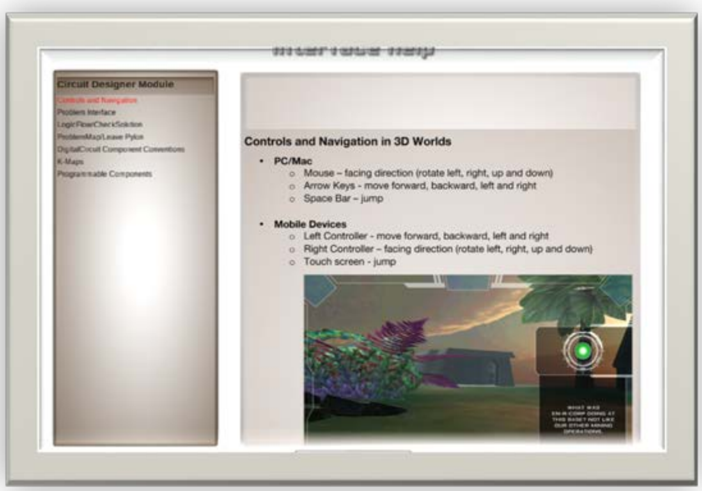

Figure 4 – Screenshot of PlanetK - Interface Help

Assessment of Student Learning

Two instruments are used for data collection: an attitude survey and a conceptual test. Also data is collected on the total (required and optional) number of problems completed by each player. This section discusses the results of the conceptual test and game play data for students who played the game at Texas A&M University and conceptual test results for students who did not play the game at Prairie View A&M University. The conceptual test consists of 11 questions (23 total items) in which students solve problems about analysis and design of combinational circuits that are similar to the ones presented in the game. The same conceptual test was delivered both before and after students played the game. Items included in the pre/posttest are shown in Table 3.

In Fall 2015, two professors at Texas A&M University used the game in their *Introduction to Digital Systems* classes. Two professors at Prairie View A&M University administered the pretest and posttest to their *Logic Circuits* classes but their students did not play the game. The students at Prairie View A&M University will be used as a control group for Prairie View A&M University. In Spring 2016, another professor at Texas A&M University used the game in his *Introduction to Digital Systems* class. In future semesters, a control group will be added for Texas A&M University and a game play group will be added for Prairie View A&M University. Below are descriptions of the implementation of the game and pretest and posttest in the courses. In Fall 2015 and Spring 2016, the study was implemented in a similar manner.

In fall 2015 and spring 2016, students at Texas A&M University played the game as a part of their homework assignment. The game actively monitors and records every game action and the progress of the players within the game. During game play, the game stores the data on our MS SQL server under several variables including time spent in each problem, problem solutions, gate information, component usage, etc. During the first week of the semester, students were informed about how their game performance would be evaluated and graded. To assess student performance in the game, we used the number of required problem solved within the game. Table 8 shows how students' performance is presented in the game for students to monitor their progress. A cumulative score was generated for each student based on their performance in the game. Then, this cumulative score was converted to a letter grade y their professor for each student.

The course learning outcomes of the Introduction to Digital Systems course at Texas A&M University include the following: (1) ability to analyze and design combinational logic circuits, (2) ability to analyze and design sequential logic circuits, (3) ability to design high-level digital systems using Register-Transfer Level (RTL) design, and (4) utilize the Verilog hardware design language, logic simulation, and Field Programmable Gate Array (FPGA) technology to implement combinational, sequential, and RTL- based digital systems. The relationship of the course outcomes to the ABET outcomes are shown in Table 2.

Table 1. Learning Objectives for *PlanetK video game*

<table>
<tr><th>Learning Obj. #</th><th>World</th><th>Setting</th><th># of Pylons</th><th># of problems</th><th>Concepts</th><th>Learning/Instructional Objectives</th></tr>
<tr><td>1.</td><td>0</td><td>Alien Forest</td><td>1</td><td>13 (spring 2015)

7 (fall 2015)</td><td>Gates, Truth Table, Boolean Expressions, Logic operators</td><td>Be able to identify logic gates, and analyze the operation of a circuit of logic gates.</td></tr>
<tr><td>2</td><td>1</td><td>Abandoned Communications Complex</td><td>7</td><td>34 (spring 2015)

31 (fall 2015)</td><td>AND-OR Circuits
OR-AND Circuits
NOR Circuits
NAND Circuits</td><td>Be able to design combinational circuits using logic gates: AND, OR, NAND, & NOR.</td></tr>
<tr><td>3</td><td>2</td><td>Transport Station</td><td>6</td><td>30 (spring 2015)

28 (fall 2015)</td><td>2-var k-map
3 & 4-var K-maps
3&4 w/ Don’t Cares K-maps
5-var K-maps</td><td>Be able to apply Karnaugh Maps, up to six variables, as a tool in designing combinational circuits. Be able to describe the relationships between operations performed using these tools and equivalent Boolean algebraic manipulations.</td></tr>
<tr><td>4</td><td>3</td><td rowspan="2">The SS Aprille Erickson</td><td rowspan="2">14 (spring 2015)

13 (fall 2015)</td><td rowspan="2">81 (spring 2015)

53 (fall 2015)</td><td rowspan="2">Adders - 2's comp.
Subtractors - 2's comp
MUX, Decoders, PROM, PLA, PAL (single and multi-bit) components</td><td>Using combinational circuitry, be able to analyze and design standard arithmetic circuits that involve signed addition, subtraction, and multiplication</td></tr>
<tr><td>5</td><td>3</td><td>Be able to analyze and design combinational digital circuits using building blocks such as multiplexers, ROMS, PLAs, PALs, and decoders</td></tr>
<tr><td>6.</td><td>4</td><td colspan="3" rowspan="2">To be developed in future</td><td rowspan="2"></td><td>Be able to use concepts of combinational and sequential circuits in design</td></tr>
<tr><td>7.</td><td>5</td><td>Be able to analyze and design standard synchronous sequential circuits using primitives such as latches, flip-flops, registers, and counters</td></tr>
</table>

Table 2. Relationship of Course Outcomes at Texas A&M University to ABET Outcomes

Course Activity	Assessment Method	ABET Outcome
Application of set theory to understanding Boolean algebra	Homework problems and exam questions	3(a)
Design of combinational digital circuits	Homework and ***PlanetK*** problems (including *PlanetK* pre and post tests) and exam questions	3(c), 3(e)
Design of sequential digital circuits	Homework problems and exam questions	3(c), 3(e)
Laboratory experiments involving Verilog programming	Laboratory assignments	3(c), 3(k)
Understanding digital systems based on digital design principles	Final laboratory and exam questions	3(a), 3(c)

Below are the details of how the game and tests were implemented in the classes at Texas A&M University in Fall 2015 and Spring 2016 semesters.

- all students took pretest near the beginning of semester
- all students played PlanetK (In fall 2015 semester, students were assigned to play the game for the full semester; in spring 2016 semester, students were assigned to play only for 4 weeks)
    - students were randomly assigned one of the help types (text or video)
- students played the game on their personal computers, devices, or university computers in addition to other homework assignments
- professors gave deadlines for completion of each world
- professors assigned a grade for each world
- all students took posttest by the end of the semester in fall 2015 and after the deadline of the final stage of the game in spring 2016
    - posttest and game scores counted as a grade for the semester

Below are the details of how the tests were implemented in the classes at Prairie View A&M University in fall 2015 which did not use the game.

- all students took pretest at beginning of semester
- professors assigned regular homework and used normal grading procedures
- all students took posttest near the end of the semester
- posttest counted as a grade for the semester

Tables 4-7 present the pretest and posttest scores and gameplay data for the studies performed at the two institutions. The data is being used to improve the conceptual test questions and problems in the game.

Table 3. Pre/Post Test Content and Rubric

Question Number	Learning Objective #	Item Objective	Scoring
1	3	Design two level circuit	Three parts at 5 points each
2	2	Analyze two level circuit	5 points for correct multiple choice answer
3	2	Design two level circuit using NAND gates	Three parts at 5 points each
4	3	Design minimum two level product of sums using Kmap	Three parts at 5 points each
5	4	Analyze circuit with adders	5 points for correct multiple choice answer
6	4	Design circuit with adders	5 points for correctly completing wiring in circuit
7	4	Design circuit with adders	Three parts at 5 points each
8	5	Design circuit with multiplexers	One step, 5 points
9	3, 5	Design circuit with multiplexers	Three parts at 5 points each
10	5	Design circuit with decoders	5 points for correctly completing wiring in circuit
11	5	Design circuit with Programmable logic device	Three parts at 5 points each
	Total		**115 points**

Table 4. Test Scores and Game Play Data – Professor 1, Texas A&M University- Fall 2015

Professor One at Texas A&M University							
	# of students	Avg Pretest Scores (23)	Avg Posttest Scores (23)	Average # of required problems solved in World 1 (19)	Average # of required problems solved in World 2 (17)	Avg # of required problems solved in World 3 (37)	Avg # of required problems solved in all worlds (79)
Students who played game	33	3.63	11.27	17.27	11.03	7.18	41.03
Students who did not play game	5	2.4	7.6	0.6	0	0	5.4

Table 5. Test Scores and Game Play Data – Professor 2, Texas A&M University – Fall 2015

Professor Two at Texas A&M University							
	# of students	Avg Pretest Scores (23)	Avg Posttest Scores (23)	Average # of required problems solved in World 1 (19)	Average # of required problems solved in World 2 (17)	Avg # of required problems solved in World 3 (37)	Avg # of required problems solved in all worlds (79)
Students who played game	24	0.67	13.67	17.41	9.87	14.5	47.37
Students who did not play game	1	0	10	1	0	0	7

Table 6. Test Scores and Game Play Data – Professor 3, Texas A&M University – Spring 2016

Professor Three at Texas A&M University							
	# of students	Avg Pretest Scores (23)	Avg Posttest Scores (23)	Average # of required problems solved in World 1 (19)	Average # of required problems solved in World 2 (17)	Avg # of required problems solved in World 3 (37)	Avg # of required problems solved in all worlds (79)
Students who played game	99	0.63	9.65	17.4	14.2	20.7	58
Students who did not play game	0	0	0	0	0	0	0

Table 7. Test Scores – Professor 1 & 2, Prairie View A&M University

Prairie View A&M University			
	# of students	Avg Pretest Scores (23)	Avg Posttest Scores (23)
Professor One's class	22	0.45	4.68
Professor Two's class	17	0.47	9.06

Conclusions

This paper discusses an ongoing educational research project which includes the development of a video game, *PlanetK*, to improve the learning of digital systems concepts in digital systems and computer architecture courses, and studies with students at two institutions, Texas A&M University and Prairie View A&M University, in Fall 2015 and Spring 2016. Students were given a pretest and posttest to assess their learning in relation to the learning objectives addressed by the video game. Further data was collected on the number of required problems solved in the various stages of the game in relation to the learning objectives of the game. The effectiveness of the conceptual test and game problems were evaluated and the results are being used to continuously improve their fidelity. While the results are very preliminary and the game is still under development, the results demonstrate the potential of the video game to improve the learning of students in digital systems and logic circuits courses.

Table 8 Accomplishments (Status)

World	Topic	Pylon #	Total # of Tasks	# of Tasks Completed	# of Required Tasks	# of Required Tasks Completed	# of Required Tasks Completed
World 0	Basic Gates	**0.A**	7	6	6	6	1
World 1	AND-OR Gates	**1.A**	4	4	2	2	0
	AND-OR Gates	**1.B**	4	4	2	2	0
	OR-AND Gates	**1.C**	4	4	2	2	0
	OR-AND Gates	**1.D**	4	2	2	2	0
	NOR Gates	**1.E**	6	3	4	3	1
	NAND Gates	**1.F**	6	4	4	3	1
	Star Problems	**1.G**	3	4	3	3	3
World 2	K-Map - Simplify Logic	**2.A**	6	4	3	2	2
	K-Map - Simplify Logic	**2.B**	6	4	4	1	2
	K-Map - Simplify Logic	**2.C**	6	2	3	2	2
	K-Map - Simplify Logic	**2.D**	6	5	3	3	3
	Star Problems	**2.E**	2	2	2	2	2
	Star Problems	**2.F**	2	2	2	2	2
World 3	Adders - 2's comp.	**3.A**	6	6	5	4	0
	Subtractors - 2's comp	**3.B**	5	3	3	1	2
	MUX w/gates	**3.C**	4		2		
	MUX	**3.D**	6		4		
	MUX / Multi-bit MUX	**3.E**	4		2		
	Decoders/Multi-bit Decoders	**3.F**	6		4		
	Multi-bit Decoders	**3.G**	4		3		
	PROM	**3.H**	4		3		
	PLA	**3.I**	5		4		
	PAL	**3.J**	5		3		

World	Topic	Pylon #	Total # of Tasks	# of Tasks Completed	# of Required Tasks	# of Required Tasks Completed	# of Required Tasks Completed
	Star (ADD/SUB)	**3.K**	1		1		
	Star (MUX)	**3.L**	1		1		
	Star (Decoder)	**3.M**	1		1		
	Star (PLD)	**3.N**	1		1		
		TOTAL	**119**	**59**	**79**	**40**	**21**

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