Designing an Assessment for Introductory Programming Concepts in Middle School Computer Science

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ABSTRACT

Teaching of computer science (CS is rapidly expanding in schools. Learning to program is a key ingredient of school CS curricula, and consequently, there is a need for quality measures of student learning of foundational programming concepts. However, high-quality tools for measuring student learning in introductory CS have been under-developed and under-researched. This experience report shares the process of design and refinement of a summative paper-based assessment (that could also be administered online) for introductory programming in middle grades (6–8). We share our experiences with the use of assessment as a pre-post measure in a middle school introductory programming course in diverse, urban school classrooms in the US and use that data to conduct validity, reliability and item discrimination analyses.

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1 Introduction

In recognition of our fast-changing world that is driven by computing, efforts to introduce Computer science (CS) as a new STEM discipline to all students in K-12 is rapidly gaining momentum, both nationally and globally. Programming is seen not only as a key part of all introductory computer science learning, but as a crucial 21st century skill that can motivate and empower young learners to be creative and digitally fluent, as well as enrich learning in all subjects. Introductory programming experiences aim to provide learners with engaging early experiences to help them develop an understanding of foundational computing concepts such as loops, conditionals, variables, expressions, in addition to providing an exposure to easy-to-use engaging programming experiences to help spark young learners' interest in computing [2]. Without valid measurements, however, it is difficult to know whether students are indeed developing an understanding of key concepts. Development of high-quality assessments has sadly not

kept pace with the spread of CS programs and curricula [40] and is often called out as one of the key R&D imperatives for computing education [6,12,41]. With growing availability of CS assessments at the high school level, the need for robust measurement—for both formative and summative purposes—is now acutely felt at the middle and primary school levels [7]. Additionally, although the goal of designed assessments is always to measure student learning, it need not be done with the sole aim of grading students [15]. In these nascent years of teaching CS in formal classroom settings, aggregated data from even summative assessments can be very useful to evaluate curricula, pedagogy, and progress of student learning in the K-12 years and to prompt curricular revisions.

This experience report describes the design and use of a summative instrument ('VELA Assessment') for measuring learning of introductory programming concepts in grades 6–8. With the goal of designing for future repurposing of this, e.g., designing items in different languages, we used a principled assessment design methodology—Evidence-Centered Design (ECD) [25] to (a) create assessment *design patterns* [3, 16] that can be used by others to design items and (b) focus on measuring understanding of variables, expressions, loops, conditionals, and abstraction—concepts that are foundational to most introductory programming (*regardless of language*), even though we designed items involving Scratch code (that could involve other concepts such as events & broadcasts). This makes this work more generalizable than prior assessments that have focused on programming constructs in a specific programming language (e.g. [42]). After iterative rounds of piloting and refinement, the assessment was used as a pre-post measure in a middle school introductory CS class in an urban school district in USA. Classroom data were used to examine difficulty, validity and reliability. After a review of relevant work, we briefly describe our design process guided by the framework [25]. We share examples of items and item refinement before describing the results of the using VELA assessment as a pre-post measure in a middle school introductory programming intervention. The paper describes validity and reliability analyses conducted on data gathered from the classroom use data, as well as student performance at various grade levels (6, 7, & 8). Our findings suggest that this is a good instrument that, with accompanying rubrics and assessment design patterns, can serve as an important resource and tool for middle school CS teachers and researchers since the assessment design patterns and items can be used as a template to design assessments for imperative, procedural languages. The paper concludes with learnings and further guidance on the use of this assessment.

2 Related Work

This work draws on prior efforts on designing assessments for the middle school level that use multiple-choice or short-response items types (often with code snippets) and involve code-comprehension,

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debugging, writing pseudocode and evaluating code [e.g. 13,30,42]. However, those either focus heavily on programming language constructs [42] or are designed for formative use [13, 30]. There is also either no data around their use or context of use [27] or missing evidence on validity and reliability of those assessments. Additionally, some recent efforts have focused on language-agnostic assessment of *computational thinking* [e.g. 10, 39], whereas our focus is on measuring understanding of programming concepts in the vein of a concept inventory [33] or Tew & Guzdial's FCS1 assessment [35]. We are guided by the ECD design process and patterns [3] as well as the assessment created and attendant validity and reliability tests conducted in past research [32], for the high school Exploring Computer Science (ECS) curriculum [11].

We acknowledge that coding tasks and process-based measures are arguably more authentic, but they are challenging as assessment instruments [18]—scoring programming projects is subjective and time-consuming; and the mere presence of constructs in programs is not always an indication of understanding [17]. Additionally, past research has documented the benefits of well-designed multiple-choice items to target deeper understanding of programming concepts [15,20, 28,31,40]. Lastly, we believe an assessment such as this one must be combined with other measures that together comprise “systems of assessments” [15], to provide a holistic view of student understanding. This combination of measures must include programming tasks (open-ended/free-choice and closed), among other measures and tasks (such as Parson's puzzles [8,29]).

3. Designing the Assessment

Guided by ECD as a principled methodology for designing the assessment, our design process involved the following—

- Analyzing the domain of introductory programming using emergent K-12 CS standards and frameworks [5, 19] and research on middle school introductory programming [13] to articulate target concepts to be measured that are common to most programming environments.
- Developing assessment arguments known as *focal knowledge, skills, and abilities* (FKSAs) (Table 1) targeting programming concept-related abilities for which assessment items would elicit evidence [26]. Most FKSAs targeted comprehension and application levels of Bloom's Taxonomy [36], with a few targeting higher analysis and synthesis levels. These FKSAs represent “design patterns” for designing various forms of assessment (e.g. involving various programming languages) that target these set of conceptual programming knowledge and skills [27]. The FKSAs were also reviewed by experts.
- Designing items based on these FKSAs and iteratively refining them based on “cognitive interviews” [38] with 6 students, and two pilots in middle school classrooms with ~200 students, teacher feedback from 4 teachers (described in [16]), and review by an English Language Learning expert for accessible language. (See Table 3 for examples of refinement).

Table 1. Each FKSA below begins with “Ability to” —

FKSAs derived from ECD & Learning Goals
1. Describe the execution that is performed by a (specific) given sequence of instructions (not including loops)
2. Describe what a given loop is doing
3. Describe the sequence that is executed in a given program when

the program contains things inside and outside of the loop.
4. Show that a loop involves a repeating pattern, that will terminate under a specified condition or after a certain number of repetitions
5. Identify the repeating pattern within a loop
6. Describe the structural components of a pattern
7. Identify a pattern from a real-world phenomenon
8. Describe how a conditional pathway would operate or create a conditional pathway
9. Create variables, assign values and update variables
10. Describe how a variable changes values in a loop
11. Use a variable within a loop
12. Identify bugs related to overwriting values of variables (i.e. understanding that a variable can only hold one variable at a time)
13. Determine what variables are required in a program to achieve the goals of the computational solution.
14. Evaluate a Boolean expression
15. Use Boolean operators (And, Or, Not) in a program
16. Create a Boolean expression for a given condition
17. Identify sub-parts of a computational solution
18. Create a Boolean expression to control a loop
19. Identify a constant vs. a variable in a program
20. Decide on an appropriate initial value for a variable
21. Create an expression using existing variables
22. Define an abstraction to represent a general solution

Table 2. Nine Items, Sub-parts & Concepts/FKSA covered

Item	FKSA	Parts	Concepts	Points
1	1, 8, 13	a	Boolean Exp.+Conditional	1
		b	Boolean Exp.+Conditional	2
		c	Boolean Exp.+Conditional	2
2	1, 8, 12	a	Conditional+Relational Exp.	3
		b	Conditional + Variables	2
3	2,3,9, 10	a	Variables + Arith. Exp + Loops	2
		b	Variables + Arith Exp + Loops	2
		c	Variables + Loops	1
4	2,3,4,8, 10, 11, 14, 15, 16,17,18, 21, 23	a	Abstraction (Pattern Gen.)	1
		b	Abstraction (Pattern Gen.)	1
		c	Abstraction (Pattern Gen.)	1
		d	Variables + Arithmetic Exp.	1
		e	Variables + Boolean Exp + Loops	1
		f	Variables+ Arithmetic Exp + Loops	2
		g	Variable + Boolean Expression	2
5	14		Boolean Expression	1
6	14		Boolean Expression	2
7	4, 8, 9, 13, 15, 16, 18, 19, 20, 21	a	Variables (V)	5
		b	Variables (V)	3
		c	Variable + Arithmetic Expression	2
		d	Variable + Arithmetic Expression	2
		e	Variable + Boolean Expression	2
		f	Variables + Arithmetic Exp + Loops	2
8	4, 5, 6, 7, 11, 22	a	Pattern Recognition	2
		b	Abstraction (Pattern Gen.)	2
		c	Loops	1
		d	Loops	4
		e	Variables + Loops	4
9	2,3,4,5		Loops	4

Table 3. Examples of items before and after refinement based on pilot studies of the assessment (a) Item #3 and (b) Items #5 & #6

when green flag clicked

say [] for 2 secs

set Number to []

set skipNumber to []

set NumberOfTimes to []

say Number for 2 secs

repeat NumberOfTimes

set Number to Number + skipNumber

say Number for 2 secs

say [] for 2 secs

say Number for 2 secs

Untitled

(b) Does the value of Number change in the loop? ☐ Yes ☐ No

• If Yes, explain how it changes. [Text box for open response]

(c) Does the value of NumberOfTimes change in the loop?

☐ Yes ☐ No

If Yes, explain how it changes. [Text box for open response]

After Piloting and Refinement

(Using responses to #3a from pilot, created multiple choice version)

Item#3 (a). After the green flag is clicked, what will the fox say?

when green flag clicked

say Let's count!

set Counter to []

set NumberOfTimes to []

repeat NumberOfTimes

say Counter

set Counter to Counter + 2

say Last number!

say Counter

Untitled

Let's count!

0

2

4

6

8

Last number!

8

☐ A. Let's count!

Counter

Last number!

☐ B. 6

8

Last number!

8

☐ C. Let's count!

0

2

4

6

8

Last number!

10

☐ D. Let's count!

Counter

Counter

Counter

Counter

Last Number!

Counter

3(b). In the program, does the value of Counter change in the loop?

☐ Yes ☐ No

If Yes, explain how it changes. [Text box for open response]

3(c). In the program, does the value of NumberOfTimes change in the loop?

☐ Yes ☐ No

If Yes, explain how it changes. [Text box for open response]

(Before Revision) Item #5:(a) Select all pictures that match the Boolean condition where something has “legs OR wings.”

☐

☐

☐

☐

Item #5:(b) Select all pictures that match the Boolean condition where something has “legs AND wings.”

☐

☐

☐

☐

Item #6: In the table below, check all of the words that satisfy each condition.

Logical Expression	Words	
• (Starts with a D) AND (ends with an E)	☐ DANCE ☐ DELICIOUS	☐ SOCCER ☐ SHARE
• (Starts with a D) AND does NOT (end with an E)	☐ DANCE ☐ DELICIOUS	☐ SOCCER ☐ SHARE
• (Starts with a D) OR (ends with an E)	☐ DANCE ☐ DELICIOUS	☐ SOCCER ☐ SHARE
• (Starts with a D) OR does NOT (end with an E)	☐ DANCE ☐ DELICIOUS	☐ SOCCER ☐ SHARE

After Piloting and Refinement

(Feedback: Item#5- Students interpret images in ways we don't! Item#6- Adults in the lab also got some wrong - they're confusing!)

Item #5. Kathy takes an umbrella to school if it is raining. She also takes an umbrella if it is cloudy. She does not take an umbrella for any other weather. Which Boolean expression shows this?

☐ Take umbrella IF (raining OR cloudy)

☐ Take umbrella IF (raining AND cloudy)

Item #6: When the car is running it beeps a warning if your seatbelt is not fastened.

Which Boolean expression shows this?

☐ Warning beep IF ((Car running) OR (NOT Seatbelt fastened))

☐ Warning beep IF ((Car running) AND (NOT Seatbelt fastened))

☐ Warning beep IF ((Car running) OR (Seatbelt fastened))

☐ Warning beep IF ((Car running) AND (Seatbelt fastened))

Table 4. New items (#7 & #8) added after piloting to address coverage of FKSAs and deeper conceptual understanding

Item #7: You are programming a maze game. The screen shows a cat, maze walls, and gold coins. You make a cat move around the screen trying to find gold coins. The maze walls and coins stay in the same location every time you play the game.

- You start with a score of 0.
- You have 5 lives at the start.
- If the cat touches a gold coin-
 - You gain a life, and
 - your score increases by 100.
- If the cat touches a wall-
 - you lose a life, and
 - your score decreases by 100.

The game ends when you reach a score of 500 or no lives are left. If your score is 500 when the game ends, you win. If your score is less than 500 when the game ends, you lose.

a. For each of the following, does it change as you play the game?

Score	☐ Changes	☐ Does not change
Lives	☐ Changes	☐ Does not change
Wall	☐ Changes	☐ Does not change
Coins	☐ Changes	☐ Does not change
Cat's Position	☐ Changes	☐ Does not change

b. Describe 1 variable that is needed to program this game.

- What would you name the variable?
- Describe the purpose of the variable.
- What is the starting value of the variable?

Variable Name	Describe how this variable is used in the program (what is the purpose of this variable)	Starting value of the variable

c. What happens when the cat touches a gold coin?

- Use the IF block below (and variables 'Score' and 'Lives')
- Write the expressions one below the other to show how the value of the variables in the game changes.

if touching gold coin ? then

d. What happens when the cat runs into a Wall?

- Use the IF block below (and variables 'Score' and 'Lives')
- Write the expressions one below the other to show how the value of the variables in the game changes.

if touching wall ? then

e. When does the game end? Use the following Repeat Until loop to write an expression to decide when the game ends.

repeat until

f. Write an "If" statement to decide if the player has won or lost. (Use variables)

Item #8: A pattern is shown below.

★ ★ ▲

Step 1

★ ★ ▲ ▲

Step 2

★ ★ ▲ ▲ ▲

Step 3

a. Draw the next step (**Step 4**) in the pattern [Open-response]

b. Describe in words what the pattern would look like for **Step 600** [Open response text box]

c. If you were write a program to produce **Step 600** of this pattern, check mark which ONE of the following Scratch blocks that you would need:

if then else

repeat

forever

wait secs

say

d. The following program draws **Step 2** of the pattern:

Draw a star
Move to the right
Draw a star
Move to the right
Draw a triangle
Move to the right
Draw a triangle

Now write a program to draw **Step 600** of the pattern. Use the Scratch block you picked in part c. You may use the **Move** and **Draw** commands as shown above. [Open-response text box]

e. Now, write a "pattern generator" program to draw the pattern for ANY Step number a user inputs. You may use the **Move** and **Draw** commands as shown above, along with Scratch commands.

The first part of the program looks like this—

when clicked

ask What step of the pattern do you want to draw and wait

set StepNumber to answer

In the code snippet above, *StepNumber* is a variable whose value is set to whatever a user inputs (in the **Ask** command).

Continue the program below. Use *StepNumber* in your program instead of a value of a particular step. --

ask {What step of the pattern do you want to draw?} and wait

set StepNumber to answer

Item #4: Kayla is saving money to buy a new bicycle. Kayla has six (6) uncles. On Kayla's birthday, each uncle gave her some money to help her buy the bicycle. To figure out if she has enough money to buy the bicycle, Kayla creates the following program:

The program has been divided into three sections (A, B and C). In the table below, match the section of the program (A, B or C) to the description of what it does--

What the program does:	Section of program?
a. Sums up the amount of money that Kayla receives from her uncles	☐ A ☐ B ☐ C
b. Compares that amount to the price of the bicycle and tells Kayla whether or not she has enough money to buy the bicycle.	☐ A ☐ B ☐ C
c. Tells Kayla to enter the price of the bicycle	☐ A ☐ B ☐ C

Figure 1. Item#4 adapted to add identification of problem sub-parts

Finally, a paper-based assessment (also administerable online) to be completed over the course of a 45-50-minute class period was finalized (*free for authorized educators at edfinity.com*). It contains 9 multiple-choice and open-response items (with 29 individually scored sub-items). Table 2 reflects coverage by FKSA and concepts as well as assigned scores by sub-item. Some items (e.g., #2 and #4) were adapted from items in the Israel national exam for middle school [42] and some from prior research in middle school CS [13]. Fig. 1 shows item #4 adapted from [42] to add questions related to identifying sub-parts of a program (to address FKSA 17).

4. Use of Assessment in Classroom

We used the assessment as a pre-post measure for our introductory programming CS intervention involving 74 students in three classrooms (6th, 7th, and 8th grade) in an urban school district in Western US. These 3 classrooms reflected their schools' diversity in ethnicity, socio-economic status, and academic preparation (as measured by English and math scores on state-wide tests). In general, Grade 7 students belonged to a high socio-economic group and a high-achieving school with majority students at or above grade level in math and English, whereas both grades 6 and 8 largely comprised students identified as low socio-economic status, with high percentages at below-grade level in math and English state tests (see Table 5). All three classrooms were taught the same Scratch-based curriculum (described in [19]) that included activities designed to provide learners conceptual engagement with the foundational concepts (conditionals, loops, variables, expressions Boolean operators, and abstraction (by creating new variables using expressions and existing variables). The pre-post assessments were scored based on a rubric (e.g., see Fig 2. for item #9 scoring rubric).

Table 5. Student and school sample characteristics

	Grade 6	Grade 7	Grade 8
Male	17	15	11
Female	9	16	3
School characteristics (from district website)			
Low SES	85%	40%	87%
Math Proficiency	55%	79%	34%
English Proficiency	54%	80%	41%
Learning Disabilities	12.8%	3.5%	15%

* 3 students dropped due to lack of pre-post assessment data

Item #9: What does the fox say when the green flag is clicked?

4 points Let's Start! Hello! Goodbye! Hello! Goodbye! Hello! Goodbye! Hello! Goodbye! Finished!	3 points Hello! Goodbye! Hello! Goodbye! Hello! Goodbye! (missing Let's Start! or Finished! or both)	1 point Correct Let's Start! and Finished! but incorrect loop part (no repetition, or grouped loop)
0 for all other responses		
(No penalty for missing exclamation points)		

Figure 2. Rubric showing scoring for item #9

Figure 3. Average scores on each item by grade

4.1 Results

Average post-scores were **53%, 80%, 69%** for Grades 6, 7, & 8, each of which were significantly higher than average pretest scores (**39%, 66% & 56%** respectively). Grade level was positively correlated with score for grades 6 & 7. Grade 8 performed worse than Grade 7, *however overall posttest scores were significantly and positively correlated to students' prior English and Math scores on state assessments*. The assessment appeared to be difficult for Grade 6. Item-wise analysis by concepts and grade (Fig. 3, 4) revealed that grade 6 struggled more with combinations of concepts than did grade 7. Item #6 was the easiest for all. **Item #2 was difficult for all students (due to poor wording) and needed revision.** However, it is important to remember that several factors contribute to student performance in addition to the assessment itself, including the curriculum, teacher CS experience and expertise, and students'

background and academic preparation. Our grade 6 student sample comprised low-performing students compared to grade 7.

Figure 4. Average concepts-wise scores by grade

4.2 Validity, Reliability, Discrimination and Difficulty Analyses of Assessment & Items

The domain analysis and modeling phases of the ECD design process help establish a baseline level of test validity [25] as do student responses in cognitive interviews. Current conceptions of test validity also see reliability as integral to validity [1]. Factor analyses on our classroom use data (from all three grades) revealed that the assessment was measuring *one overall factor* suggesting *high internal consistency among the items*. The assessment items reflected a *high level of reliability at 82%*. The *Discrimination Index (DI)* of an item (or assessment) reflects how well an item (or assessment) differentiates between high and low scorers. *Item discrimination analysis revealed that items targeting combinations of programming concepts rather than individual concepts (Items #4, #7, #8, #9) had higher discriminatory power*. The Discrimination and Difficulty Index (average score across all grades) and of each item are shown in Table 6. *It is worth noting that Item#9 (Fig 2) has the highest DI. It demonstrates the value of a relatively easy and simple item in revealing conceptual understanding or the lack thereof, of a key concept such as loops (as in a concept inventory).*

Table 6. Item-wise difficulty and discrimination indices

	#1	#2	#3	#4	#5	#6	#7	#8	#9
Difficulty (Avg. score)	.86	.35	.54	.63	.84	.90	.71	.69	.71
Discrimination	.37	.62	.46	.61	.35	.20	.51	.50	.68

5. Discussions, Reflections & Lessons Learned

Besides the creation of a valuable tool, there are many takeaways and lessons learned from this process and experience report.

Based on validity, reliability, difficulty and discrimination analyses of the items and instrument, the assessment represents a solid early attempt as a measure of introductory programming concepts. The significant increase from pre-to-post intervention shows that the assessment is sensitive to instruction (another key criterion for test validity). Assessment literature views DIs between 0.25 and 0.39 as good and those above 0.40 as excellent [4,22]. This assessment is of medium difficulty. Given the findings in the context of the three classrooms that used the assessment, and the lower performance of Grades 6 & 8 (which not only had students with poor academic preparation but also uneven sample sizes), *the assessment should be*

used in other settings to understand its quality more broadly. The difficulty (especially for 6th graders) of certain items is consistent with levels of Bloom's taxonomy. While Items #1, #5, and #6 dealt with single concepts and comprehension/application, Items #4, #7, #8, & #9 involved combinations of concepts and captured analysis and synthesis of programming concepts. Use of this assessment with grade 6 should be done keeping these data in mind.

This assessment contains a mix of multiple-choice as well as open-response item types involving Scratch (one of the more popular environments for introductory programming in middle grades). Our rubrics provide detailed guidelines for partial grading of open-response items. Although giving partial credit in open-ended items makes scoring more complex and time-consuming, an assessment that includes some open-response items that require students to write pseudo-code, construct expressions, or provide explanations makes for a richer assessment and helps provide better evidence of student understanding than multiple-choice items alone.

It is important to note that several factors contribute to student performance in an assessment, including (among others) the CS curriculum, teacher CS experience and expertise, and students' background and academic preparation [14]. *It is therefore crucial that such an assessment not be the only measure for "grading" a student at the end of the course*, but one of many varied forms of assessment (such as final projects among other tasks, and measures of attitudes and interest) that can provide a holistic measure of student learning and engagement [15]. This is important since desired outcomes for current CS initiatives include students' conceptual growth and also affective measures such as identity development, motivation, and engagement [19].

The reasons for using ECD included the inbuilt validity & in-process alignment, the creation of generalizable design patterns that can be used for creating other assessments from the same FKSA, and the availability of a prior example of its use for the design of a high school CS assessment [32]. Note that we did not consider the SOLO taxonomy used in some CS assessment research [21] as it defines levels in terms of responses a student may give to a task which was not aligned with this effort. CS researchers have also found Bloom's Taxonomy to be difficult to apply consistently to assessment tasks in introductory programming courses [9].

In summary, this paper shares a robust summative assessment for middle school CS for middle school CS and describes the experience of creating such a tool *focused primarily on introductory programming concepts*. The multi-layered design process guided by ECD, a principled assessment design approach, ensures alignment between items and target focal knowledge, skills, & abilities. We discuss key features of the assessment as well as almost all the items and share examples of scoring rubrics. This work and paper make a significant contribution to the field, benefiting students, teachers and administrators working in the uncharted-yet-rapidly-expanding realm of teaching CS as new subject in K-12 classrooms. The design process ensures broad use for this instrument, its accompanying rubrics, and the assessment design patterns developed, which can also guide adaptation of items to other programming languages. Our next steps involve refining Item#2 and testing more broadly with larger and diverse student samples.

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